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LEVEL II

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COMPUTER SIMULATION OF EJECTION SEAT PERFORMANCE AND PRELIMINARY CORRELATION WITH EMPIRICAL DATA

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Crew Escape and Subsystems Branch
Vehicle Equipment Division

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The comparison of six-degree-of-freedom computer program modeling ejection seat performance to empirical data from ejection seat track tests is discussed. The computer subroutines model the ejection seat components which generate forces on the seat and crewperson combination during ejection. The resulting motion described in terms of trajectory parameters, as well as acceleration time histories on the ejectee is correlated with measured data from recent Air Force track test programs in which ejection seat performance was determined.

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FOREWORD

This report describes an in-house effort conducted by personnel of the Crew Escape and Subsystems Branch (FER), Vehicle Equipment Division, Air Force Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 2402, "Vehicle Equipment Technology," Task 240203, "Aerospace Vehicle Recovery and Escape Subsystems," Work Unit 24020312, "Crew Escape and Recovery System Performance Assessment."

The work reported herein was performed during the period of 1 October 1977 to 1 February 1979 by the author, Mr. Lanny A. Jines (AFFDL/FER), project engineer. The report was released by the author in June 1979.

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LIST OF SYMBOLS

SYMBOL	UNITS	DEFINITION
DRI	Non-Dimensional	Dynamic Response Index.
GX	Non-Dimensional	Acceleration along the body X-axis divided by the acceleration of gravity.
GY	Non-Dimensional	Acceleration along the body Y-axis divided by the acceleration of gravity.
GZ	Non-Dimensional	Acceleration along the body Z-axis divided by the acceleration of gravity.
IXX	SLug-Ft^2	Mass moment of inertia with respect to the body X-axis.
IYY	SLug-Ft^2	Mass moment of inertia with respect to the body Y-axis.
IZZ	SLug-Ft^2	Mass moment of inertia with respect to the body Z-axis.
IXY	SLug-Ft^2	Mass product of inertia with respect to the body X-Y Plane.
IXZ	SLug-Ft^2	Mass product of inertia with respect to the body X-Z plane.
IYZ	SLug-Ft^2	Mass product of inertia with respect to the body Y-Z plane.
P	Degrees/Sec	Roll rate, the angular velocity about the body X-axis.
Q	Degrees/Sec	Pitch rate, the angular velocity about the body Y-axis.
R	Degrees/Sec	Yaw rate, the angular velocity about the body Z-axis.
SRP	Non-Dimensional	Seat Reference Point, the reference point on the ejection seat defined as lying on the X-Z plane of symmetry at the intersection of the compressed seat back tangent plane and the compressed seat bucket tangent plane. The SRP is the origin of the body axes system.

LIST OF SYMBOLS (CONTINUED)

SYMBOL	UNITS	DEFINITION
TOC	Seconds	Time of catapult ignition.
XCG	Inches	X-axis location of the seat and crewperson center of gravity (c.g.) relative to an orthogonal axis system with origin at the SRP.
XEARTH	Feet	X-axis location of the seat and crewperson SRP relative to a fixed orthogonal axis system with an origin fixed by initial conditions (I.C.).
YCG	Inches	Y-axis location of the seat and crewperson c.g. relative to an orthogonal axis system with origin at the SRP.
YEARTH	Feet	Y-axis location of the seat and crewperson SRP relative to a fixed orthogonal axis system with an origin fixed by initial conditions (I.C.).
ZCG	Inches	Z-axis location of the seat and crewperson c.g. relative to an orthogonal axis system with origin at the SRP.
ZEARTH	Feet	Z-axis location of the seat and crewperson SRP relative to a fixed orthogonal axis system with an origin fixed by initial conditions (I.C.).

SECTION I

INTRODUCTION

1. BACKGROUND

Digital computer programs as applied to the analytical simulation of flight vehicles have contributed much to the development of advanced operational systems for both manned and unmanned flight. The utilization of mathematical models to compute performance characteristics of aeromechanical systems represents both technical and economic benefits during engineering research and development efforts of aerospace vehicles. The vehicle flight characteristics are achieved by mathematically determining the vehicle accelerations, velocities and displacements as functions of forces and moments, both aerodynamic and non-aerodynamic in nature.

The application of generalized six-degree-of-freedom computer modeling to aircraft emergency escape system ejection seats has been limited by the lack of seat and crewperson aerodynamic coefficients and the availability of reliable track test performance data with which to compare computed results. This situation led to the initiation of wind tunnel tests during 1969 to determine the aeromechanical properties of an ejecting crewperson (see Reference 1). Both half-scale and full-scale models of the seat and crewperson geometrical shapes were tested. Body axis force and moment coefficients were determined and referenced to the defined seat reference point (SRP). Additionally, in 1969, a contracted effort was initiated to investigate crew escape from Vertical Take Off and Landing Aircraft (VTOL) (see Reference 2). This contract resulted in the assembly of various mathematical computer subroutines simulating the operation of ejection seat components into a six degree of freedom escape system trajectory analysis program.

The program, which computed the generated forces upon the seat (i.e., catapult force, drogue chute force, etc.) was titled, "Simulation and

Analysis of In-Flight Escape System Techniques (SAFEST)." The results of the study and initial program documentation are found in References 2,3,4 and 5. Data available from early track test of the ACES II ejection seat indicated that significant improvements to the computer program were necessary prior to fully determining the usefulness and capability of SAFEST. The lack of sufficient track test data from ejection seat qualification tests prevented a complete determination of accuracy for the simulation predictions of the initial SAFEST program. These circumstances led to the 1974 start of an in-house program to develop an improved state-of-the-art SAFEST computer program capable of predicting forces and moments, trajectory motion information, and analytical qualitative evaluations of escape systems and components.

To achieve the desired goal, investigation of the ejection seat mathematical models became necessary to identify errors in the application of theoretical principles, constraints or program logic. Various SAFEST subroutines were improved through corrections of logic errors. As the evaluation of the mathematical models neared completion, the High Technology (HITECH) Ejection Seat Track Test Data became available for correlation studies with the SAFEST program.

2. APPROACH

For computer correlation studies, the High Technology Ejection Seat track test data was screened and two sets of data selected. Track test Number 49E-J1F and Number 49E-I1A provided data from a high-speed forward cockpit ejection and a low-speed aft cockpit ejection respectively, utilizing the ACES II ejection seat and the 95th percentile instrumented anthropomorphic dummy crewperson. The ACES II ejection seat operational modes are defined in Table 1 and Figure 1. Figures 2, 3 and 4 depict system sequencing for ejection initiation occurring in each of the three mode environments. Test 49E-J1F represented a Mode 2 escape system sequence of events for the ejection occurring from the forward cockpit of the F-15 sled vehicle traveling at 445 Knots Equivalent Airspeed (KEAS).

TABLE 1

ACES II EVENT TIME SEQUENCE

TYPICAL EVENT TIMING	TIME (SECONDS) MODE 1	MODE 2 (A-10)	MODE 2 (F-15/F-16)	MODE 3
1 ROCKET CATAPULT FIRES	0.0	0.0	0.0	0.0
2 DROGUE DEPLOYS	NA	0.17	0.17	0.17
3 STAPAC IGNITES	0.18	0.18	0.18	0.18
4 PARACHUTE DEPLOYS	0.20	0.97	1.17	*
5 DROGUE RELEASES FROM SEAT	NA	1.12	1.32	*
6 SEAT RELEASES FROM CREWMAN	0.45	1.22	1.42	*
7 PARACHUTE INFLATES	1.8	2.6	2.8	*
8 SURVIVAL EQUIPMENT DEPLOYS	5.5	6.1	6.3	*

*SEQUENCE IS INTERRUPTED UNTIL SEAT CROSSES MODE 3 BOUNDARY THEN DEPLOYS PARACHUTE AFTER 0.82-SECOND DELAY (A-10) OR 1.0-SECOND DELAY (F-15/F-16).

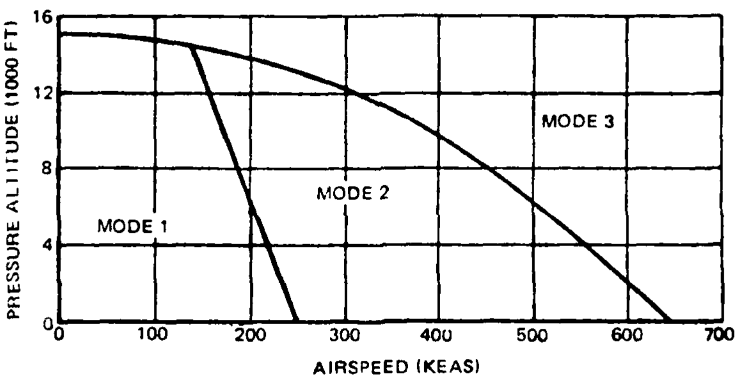


Figure 1. Mode Envelopes

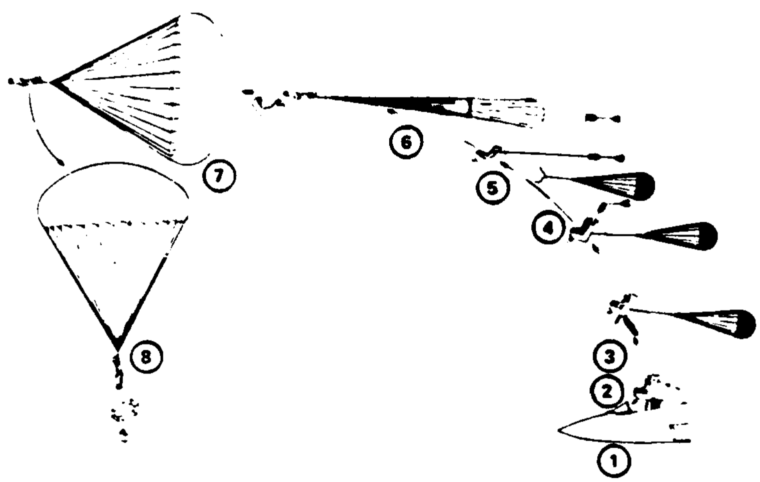


Figure 2. Mode 1 Operation

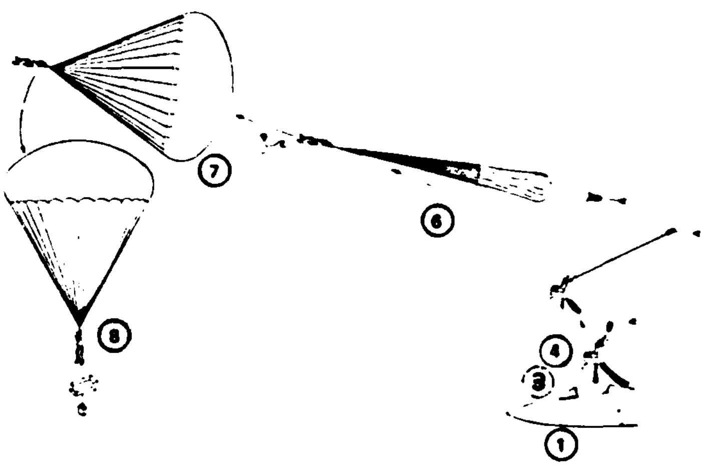


Figure 3. Mode 2 Operation

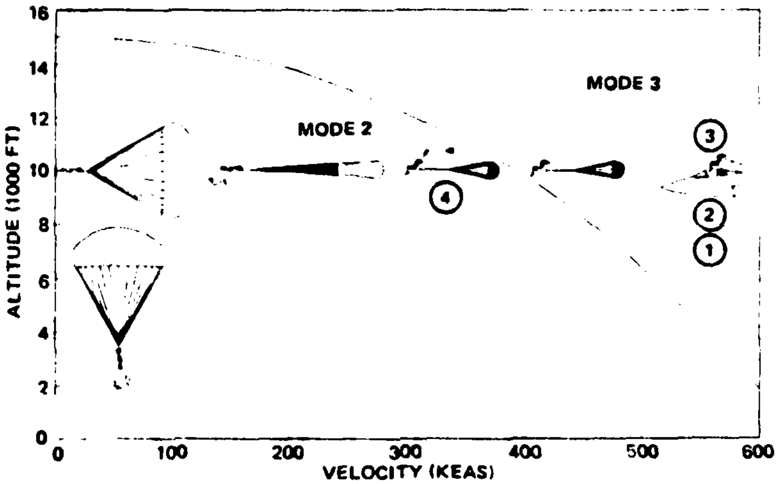


Figure 4. Mode 3 Operation

Test 49E-I1A represented the Mode 1 escape system sequence of events for the 165 KEAS ACES II ejection from the aft cockpit of the F-15 sled vehicle.

Input data decks were assembled from the ACES II manufacturer blue prints, vendor supplied component subsystem specifications, empirically measured characteristics and recorded initial conditions for the selected test to be simulated by the SAFEST computer program.

3. SCOPE

The effort to identify the accuracy of the SAFEST computer program was limited to an initial comparison of computer trajectory output parameters to the following data items measured during HITECH Tests 49E-J1F and 49E-I1A:

Longitudinal Acceleration	GX (G's)
Lateral Acceleration	GY (G's)
Vertical Acceleration	GZ (G's)
Pitch Rate	Q (DEG/SEC)
Roll Rate	P (DEG/SEC)
Yaw Rate	R (DEG/SEC)
Down Range Distance	XEARTH (FT)
Lateral Displacement	YEARTH (FT)
Altitude	ZEARTH (FT)
Catapult Pressure	(POUNDS PER SQUARE INCH)
Dynamic Response Index	DRI (Non-Dimensional)

For each test, the parameter comparisons were conducted from the time of catapult initiation until a time immediately prior to the occurrence of the recovery chute line stretch event. The total time of simulated ejection seat motion was 1.418 seconds for the 445 KEAS 49E-J1F test and 0.469 second for the 165 KEAS 49E-11A test. Prior analysis of the parachute line and inflation subroutines utilized in the computer program indicated a need for simulation improvements. As a result, correlation of the ejection seat performance during recovery chute line stretch and recovery chute inflation have been omitted. The high-speed case retains the operation of the drogue chute system for correlation studies, and resulting performance discrepancies are noted.

SECTION II

SAFEST COMPUTER PROGRAM DESCRIPTION

The SAFEST computer program computes the trajectory dynamics of an ejection seat and crewperson as it is catapulted into free flight along a set of flexible rails constrained to translate and rotate with the aircraft or track test sled vehicle. The trajectory dynamics are the result of mathematically computing the forces and moments upon the seat and crewperson during the ejection. The accelerations and rates resulting from the forces and moments are incorporated into the six-degree-of-freedom nonlinear equations and are integrated numerically by a fixed time step fourth order Runge-Kutta technique.

SAFEST includes the following identifiable mathematical models:

1. Aircraft simulation equations in six degrees of freedom to account for the aircraft induced perturbation.

2. A rail system simulation to constrain the seat as the aircraft translates and rotates while the seat moves along the rails.

3. Stabilization and deceleration systems are simulated including drogue chute, recovery parachute, gyro driven rocket (STAPAC) and aerodynamic fins.

4. Seat propulsion system equations that account for thrust variations with propellant burn rate, internal pressure, piston friction, heat loss, and grain geometry.

5. Six-degree-of-freedom equations for the seat and crewperson combination and crewperson alone for assessment of injury potential.

The aircraft subroutines utilize equations which provide for a six-degree-of-freedom simulation. The body axis equations of motion are derived from fundamental physical laws expressed as vector relations in matrix form for the computation of three angular acceleration components and three linear acceleration components. The resulting coupled acceleration components are converted to six first-order differential equations for solution by digital computer through a numerical integration algorithm. The integrated variables are the desired time histories, revealing the aircraft response to an arbitrary combination of aileron, elevator and thrust input information.

The aircraft attitude with respect to the earth is computed by integrating six of nine conventional direction cosine rates. The remaining three direction cosines are determined through an orthogonal relationship involving the six integrated rates. From the appropriate direction cosines, the Euler angles are computed.

The six-degree-of-freedom body axis equations for the seat and crewperson system which constitute the ejected mass, are derived from basic physical laws in a manner identical to the formulation of the aircraft equations. For the seat and crewperson equations, no plane of mass symmetry was assumed; therefore, products of inertia appear in the inertia tensor that are traditionally found to be negligible in aircraft equations. In addition, unlike the aircraft equations, the acceleration dependent aeroelastic coefficients are assumed to be infinitesimal. Consequently, an alternative development is used in the conversion of the coupled acceleration components to the first-order differential equation form integrable by digital computer. There is no fundamental difference in the form of the final equations or the solution algorithm.

The conventional aerodynamic coefficients are utilized for any seat and crewperson combination orientation simulation (see Reference 1). The seat attitude with respect to the earth is computed by integrating six of the nine direction cosine rates. The remaining three direction cosines are determined through an orthogonal relationship involving the six integrated rates. The Euler angles are computed from the direction cosines.

The guide rail subroutines represent an important contribution to the computer modeling to simulate the ejection seat and vehicle motion. The seat and airplane equations of motion are referenced to inertial space and, consequently, represent two completely independent systems when the catapult and rail inputs are nulled. The equations for the rail forces and moments on the seat and reactions on the airplane couple the two sets of equations.

Seat rail elasticity and contact friction through sliders or rollers are the rail parameters linking the seat and airplane. Elastic forces are transmitted to the seat computationally through a stiffness modulus matrix relating the force at each design contact point to the translation of the contact point from a neutral rail reference location. The translation is computed by integrating the seat and aircraft differential equations independently, transforming the resulting inertial space positions to the rail axis system and attributing the displacements to be proportional to the elastic restoring force components normal to the rails. The forces and associated moments at each contact point are projected back on the seat axes and, in turn, on the aircraft axes to modify the motion and to complete the interaction cycle.

The parachute equations represent any parachute translating in three degrees-of-freedom with respect to the earth and rotating with respect to attach points moving in the earth reference axes. The differential equations describe the parachute motions from an initial stowed position to full inflation. The accelerations are expressed in a form required for numerical integration by digital computer and the forces are general enough to allow evaluation of parachute performance while operating in the vicinity of a seat or crewperson.

From the stowed position, the equations allow the parachute to be projected either aerodynamically or pyrotechnically. From projection time to line stretch, the parachute accelerations are simulated as functions of mortar impulse, rocket force, lift and drag force, and deployment bag strip-off force. At line-stretch time, suspension linebridle-riser elastic forces become operative, a mass acquisition term is estimated and the growth of lift-drag forces during inflation is computed. Line reaction forces and moments are projected on the seat axes simulating the load resulting from snatch forces and opening shocks.

The seat propulsion system subroutines incorporate a thermodynamic simulation for the catapult performance and a table look up of the pressure curve for the rocket performance. For the catapulting phase, a subroutine is used which computes the performance of a closed telescoping tube, acting against a load in any acceleration environment and using a burning propellant as a source of energy. The thrust of the catapult is determined internally as a function of propellant burn rate, pressure, friction, heat loss and grain geometry.

The Dynamic Response Index (DRI) of the human spine is computed by describing the human body in terms of an analogous, lumped parameter, mechanical model consisting of a mass, spring and damper in accordance with Reference 7.

The SAFEST computer program contains 115 subroutines. A computer program flow chart of the SAFEST subroutine and Overlay structure is contained in Appendix A.

SECTION III

HITECH EJECTION SEAT TRACK TEST

1. GENERAL DESCRIPTION

During 1976, the HIGH TECHNOLOGY EJECTION SEAT TRACK TEST program was conducted at the USAF Holloman test facility in support of a source selection committee evaluation of competing ejection seats for Air Force procurement. The test included ACES II seat ejections from the A-10 single-place cockpit section at velocities of 0, 137, 151, 317, 320 and 437 Knots Equivalent Airspeed (KEAS) with various combinations of instrumented (5th-) and (95th)-percentile dummy crewpersons. Tests with the ACES II seat from the TF-15 dual place cockpit section were conducted at velocities of 0, 165, 445, 451, 634 and 637 KEAS with both 5th and 95th instrumented dummy crewpersons. For purposes of computer correlation studies, the 445 KEAS ACES II/TF-15 front cockpit position seat data was selected as a representative case of a Mode 2 ejection with a 95th-percentile dummy crewperson. This test is identified as HITECH TEST NO. 49E-J1F. Additionally, a 165 KEAS Mode 1 TF-15 aft cockpit case was selected which also had a 95th percentile dummy crewperson on board and is identified as HITECH TEST NO. 49E-I1A. Specific pretest weight information for the respective tests are contained in Tables 2 and 3. In addition to event timing and sequencing data, onboard accelerometers and rate gyro instrumentation for both seat and dummy crewperson recorded accelerations in the longitudinal, lateral, and vertical axis; and the roll, pitch and yaw rates about the respective axis. Telephoto metric optical data for space position trajectory information was also recorded. A summary of performance and event test data is contained in Table 4.

2. EJECTION SEAT DESCRIPTION

The ACES II is a lightweight advanced-technology ejection seat which has the following features (see Figure 5):

1. Three operating modes over the 0 to 600-KEAS escape envelope.

2. Automatic self-contained sensing of ejection initial conditions for recovery mode determination.

TABLE 2

HITECH 49E-J1F INITIAL CONDITIONS

EJECTION VELOCITY	445.00 KEAS
BAROMETRIC PRESSURE	25.76 IN HG
TEMPERATURE	73.8 DEG F
PERCENTILE DUMMY CREWPERSON	95.00 %
EJECTED WEIGHT BREAKDOWN:	
DUMMY CREWPERSON	195.00 LB
INSTRUMENTATION	20.25 LB
SURVIVAL VEST	13.00 LB
UNIFORM AND ACC	26.11 LB
BALLAST	5.75 LB
SURVIVAL KIT	6.00 LB
SURVIVAL KIT CONTENTS	18.00 LB
EMPTY SEAT	116.39 LB
ROCKET (NO PROPELLANT)	10.91 LB
ROCKET PROPELLANT	5.50 LB
TOTAL	406.91 LB

STATIC CG LOCATION FROM LOWER ROLLER IN RAIL AXIS
X = 12.35 IN
Y = UNKNOWN
Z = 16.57 UN
NOTE: 0.98 IN ABOVE THRUST LINE
STATIC CG LOCATION FROM SRP SEAT BACK AXIS:
X = 5.95 IN
Y = UNKNOWN
Z = 10.03 IN

TABLE 3

HITECH 49E-I1A INITIAL CONDITIONS

EJECTION VELOCITY	165.00 KEAS
BAROMETRIC PRESSURE	25.00 IN HG
TEMPERATURE	63.60 DEG F
PERCENTILE DUMMY CREWPERSON	95.00 %
EJECTED WEIGHT BREAKDOWN:	
DUMMY	170.75 LB
INSTRUMENTATION	20.25 LB
SURVIVAL VEST	13.00 LB
UNIFORM AND ACC	26.36 LB
BALLAST	20.00 LB
SURVIVAL KIT	6.00 LB
SURVIVAL KIT CONTENTS	18.00 LB
EMPTY SEAT	116.25 LB
ROCKET (NO PROPELLANT)	10.91 LB
ROCKET PROPELLANT	5.50 LB
TOTAL	407.02 LB

STATIC CG LOCATION FROM LOWER ROLLER IN RAIL AXIS:
- X = 12.53 IN
- Y = UNKNOWN
- Z = 15.55 IN
- NOTE: 0.02 IN BELOW THRUST LINE

STATIC CG LOCATION FROM SRP SEAT BACK AXIS:
- X = 6.22 IN
- Y = UNKNOWN
- Z = 9.01 IN

TABLE 4

HITECH PROGRAM TEST DATA SUMMARY

		49E-I1A	49E-J1F
TEST CONDITIONS			
EJECTION VELOCITY (KEAS)		165	445
DYNAMIC PRESSURE (PSF)		92	671
DUMMY PERCENTILE		95	95
DUMMY WEIGHT (LB)		250	250
SURVIVAL KIT WEIGHT (LB)		24	24
EJECTED WEIGHT (LB)		407	407
STATIC C.G. OFFSET (IN)		-0.02	0.90
WIND VELOCITY		10	2
WIND DIRECTION		215	150
TEMPERATURE (°F)		63.6	73.8
BAROMETRIC PRESSURE (IN HG)		25.00	25.76
SEAT PERFORMANCE			
CATAPULT MAX PRESSURE (PSI)		6851	6349
SEPARATION VELOCITY (FT/SEC)		37	35
CATAPULT MAX GZ		11.4	12.2
ROCKET MAX GZ		6.3	7.2
ROCKET MAX GX		6.8	-20.4
ROCKET MAX GY		2.1	3.6
APOGEE (FT)		70	63
DRI MAX		10.6	11.0
RADICAL MAX 110 HZ		0.69	1.26
PARACHUTE PERFORMANCE			
MAX OPENING FORCE (LB)		2371	4502
MAX LOAD FACTOR		8.6	16.4
DUMMY MAX GZ		9.0	14.5
DUMMY MAX GX		1.8	11.9
DUMMY MAX GY		-4.0	0.5
RESULTANT LOAD FACTOR		10.0	18.8
FIRST INFLATION (FT)		70	--
STEADY STATE DESCENT (FT)		13	--
DESCENT VELOCITY (FT.SEC)		20	32
EVENT TIMES (SEC)			
CATAPULT INITIATION		0	0
CATAPULT SEP./ROCKET IGNITION		.164	.174
STAPAC IGNITION		.187	.182
DROGUE GUN FIRE	1	--	--
DROGUE FULL OPEN	2	--	.385
ROCKET BURNOUT		.511	.494
STAPAC BURNOUT		.552	.552
PARACHUTE FIRST MOTION	4	.229	1.180
DROGUE RELEASE	3	--	1.306
HARNESS RELEASE		.469	1.419
LINE STRETCH	5	.528	1.600
SEAT/MAN SEPARATION		.995	1.951
FIRST FULL INFLATION		1.750	--
RECOVERY	6	4.432	--
GROUND IMPACT		5.338	4.160

TABLE 4 (CONTINUED)

HITECH PROGRAM TEST DATA SUMMARY

		49E-I1A	49E-J1F
ACTION TIMES (SEC)			
DROGUE FILL	2-1	--	--
DROGUE ACTIVE	3-2	--	.921
PARACHUTE DEPLOYMENT	5-4	.299	.420
PARACHUTE FILL	6-5	3.904	--

-- NO DATA

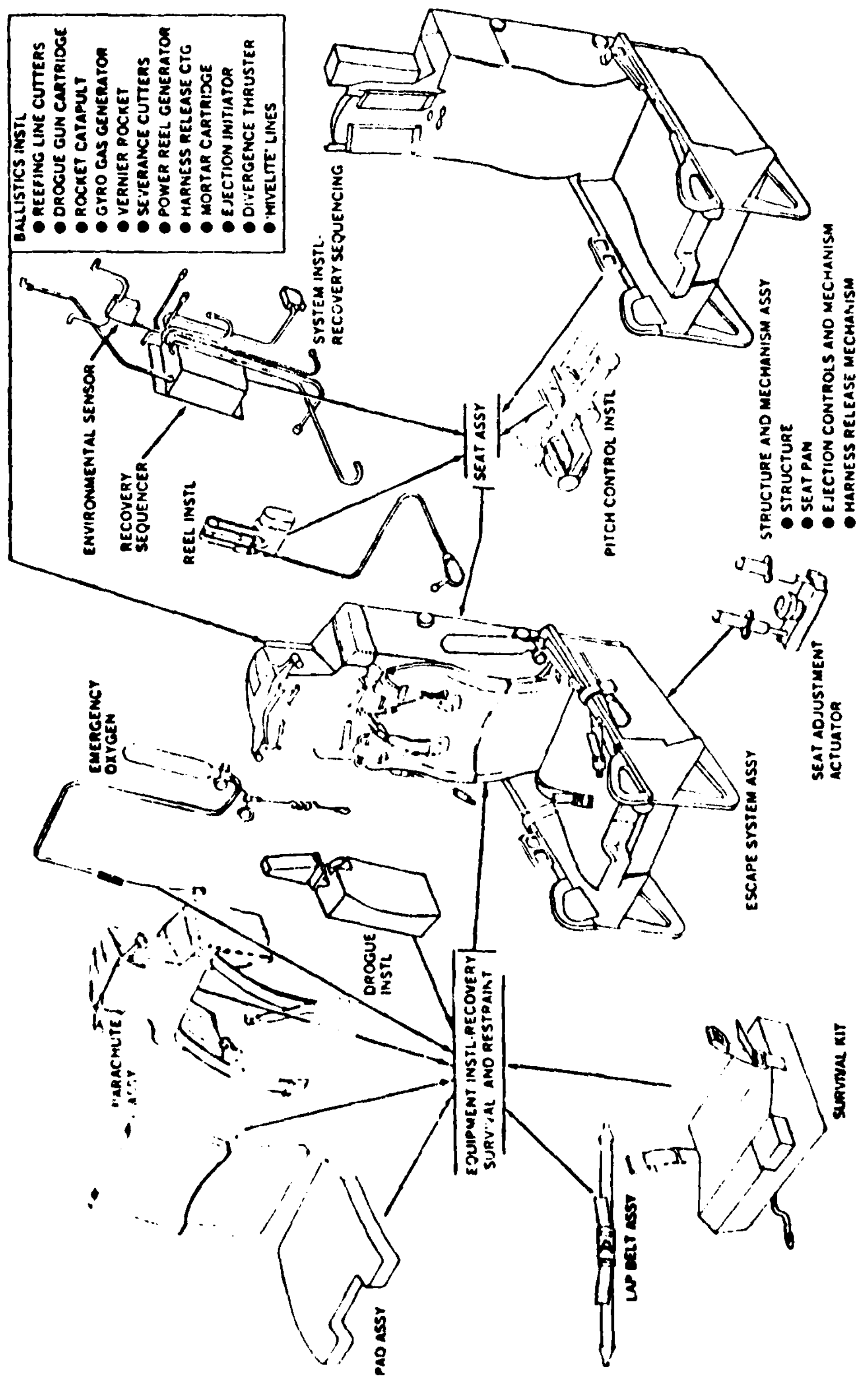


Figure 5. ACES II Subsystems

3. Electronic sequencing and timing.
4. Gyro-controlled vernier rocket for low-speed stabilization.
5. Hemisflo drogue parachute for stabilization and deceleration at high speed.
6. Mortar-deployed recovery parachute and canopy reefing.
7. Single-point emergency restraint release for rapid ground egress.

The ACES II ejection seat is primarily a monocoque structure of high-strength aluminum alloy. During ejection, the seat rollers and aircraft-mounted rails guide the seat while clearing the cockpit of the aircraft. Ejection control handles, which are interconnected so that either or both initiate the sequence, are mechanically linked to an initiator which sends a pressure signal, through a hose and disconnect, to initiate the aircraft escape system. The solid propellant CKU-5/A rocket catapult developed by the Frankford Arsenal of Philadelphia, PA, ejects and propels the seat from the aircraft. The rocket motor (sustainer) is ignited at the completion of the catapult stroke. To stabilize the seat relative to the body axis pitch plane, primarily, a gyro wheel controls deflection of a vernier rocket motor located under the seat. This unit known as "STAPAC" is operative for approximately 0.3 second from the time the seat leaves the guide rails until after the main sustainer rocket burnout. During Mode 2 and 3 recovery sequences (see Figures 3 and 4), the drogue parachute subsystem functions to stabilize and decelerate the seat and crewperson combination. A drogue gun fires a metal slug which deploys a 2.0-foot Hemisflo extraction parachute to assist deployment of the 5.0-foot Hemisflo parachute. A reefed, mortar-deployed 28-foot C-9 canopy parachute is utilized for crewperson recovery.

3. SEAT AND CREWPERSON C.G. AND INERTIA PROPERTIES

Accurate simulation of the trajectory motion of the ejected mass composed of the seat, associated subsystems and dummy crewperson requires the determination of the weight, center of gravity (c.g.) and inertia properties throughout the various configurations of weight and balance experienced during operation of the system. The SAFEST computer program continually recomputes the current weight, c.g. and inertia during the simulation of an ejection as the various subsystems of the seat are expended, deployed or jettisoned. The input information necessary to accomplish this task is obtained by measuring the weight and periods of oscillation about various axes of a seat and dummy crewperson combination on the AFFDL/FER C.G. and Inertia Meter. (See Figure 6.) For the correlation simulation study, a ninety-fifth percentile dummy was suited and ballasted to correspond to the track test instrumented dummy crewperson (see Tables 3, 4, 5 and 6). The combined seat and dummy crewperson were measured in each configuration identifiable during ejection. During the computer simulations for the correlation, the weight and c.g. location changes for the ejected payload was produced as output. Relative to the seat reference point, the longitudinal (x), lateral (y) and vertical (z) displacements of the c.g. are shown in Figures 7 and 8 for 49E-J1F and in Figures 9 and 10 for 49E-I1A. These are shown to illustrate changes in c.g. which occur during ejection. Tabulated data for the weight, c.g. and inertia properties are contained in Appendix B.

TABLE 5

SAFEST 49E-J1F INITIAL CONDITIONS

SEAT MODEL HITECH ACES II	
EJECTION VELOCITY	445.00 KEAS
BAROMETRIC PRESSURE	25.76 IN HG
TEMPERATURE	73.80 DEG F
PERCENTILE DUMMY CREWPERSON	95.00 %
EJECTED WEIGHT BREAK DOWN:	
DUMMY CREWPERSON	185.00 LBS
INSTRUMENTATION	20.00 LBS
SURVIVAL VEST	13.00 LBS
UNIFORM AND ACC	24.30 LBS
BALLAST	6.70 LBS
SURVIVAL KIT	25.30 LBS
STRUCTURE+RKT+HALF GRAIN	96.70 LBS
RECOVERY CHUTE SYSTEM	22.90 LBS
DROGUE SYSTM (SLG/EXTR/CHT)	9.10 LBS
HALF GRAIN PROPELLANT	2.80 LBS
	+--------
TOTAL(SIMULATION)	405.80 LBS

TABLE 6

SAFEST 49E-11A INITIAL CONDITIONS

SEAT MODEL HITECH ACES II	
EJECTION VELOCITY	165.00 KEAS
BAROMETRIC PRESSURE	25.00 IN HG
TEMPERATURE	63.60 DEG F
PERCENTILE DUMMY CREWPERSON	95.00 %
EJECTED WEIGHT BREAK DOWN:	
DUMMY CREWPERSON	185.00 LBS
INSTRUMENTATION	20.00 LBS
SURVIVAL VEST	13.00 LBS
UNIFORM AND ACC	24.30 LBS
BALLAST	6.70 LBS
SURVIVAL KIT	25.30 LBS
STRUCTURE+RKT+HALF GRAIN	96.70 LBS
RECOVERY CHUTE SYSTEM	22.90 LBS
DROGUE SYSTM(SLG/EXTR/CHT)	9.10 LBS
HALF GRAIN PROPELLANT	2.80 LBS
	+-------
TOTAL(SIMULATION)	405.80 LBS

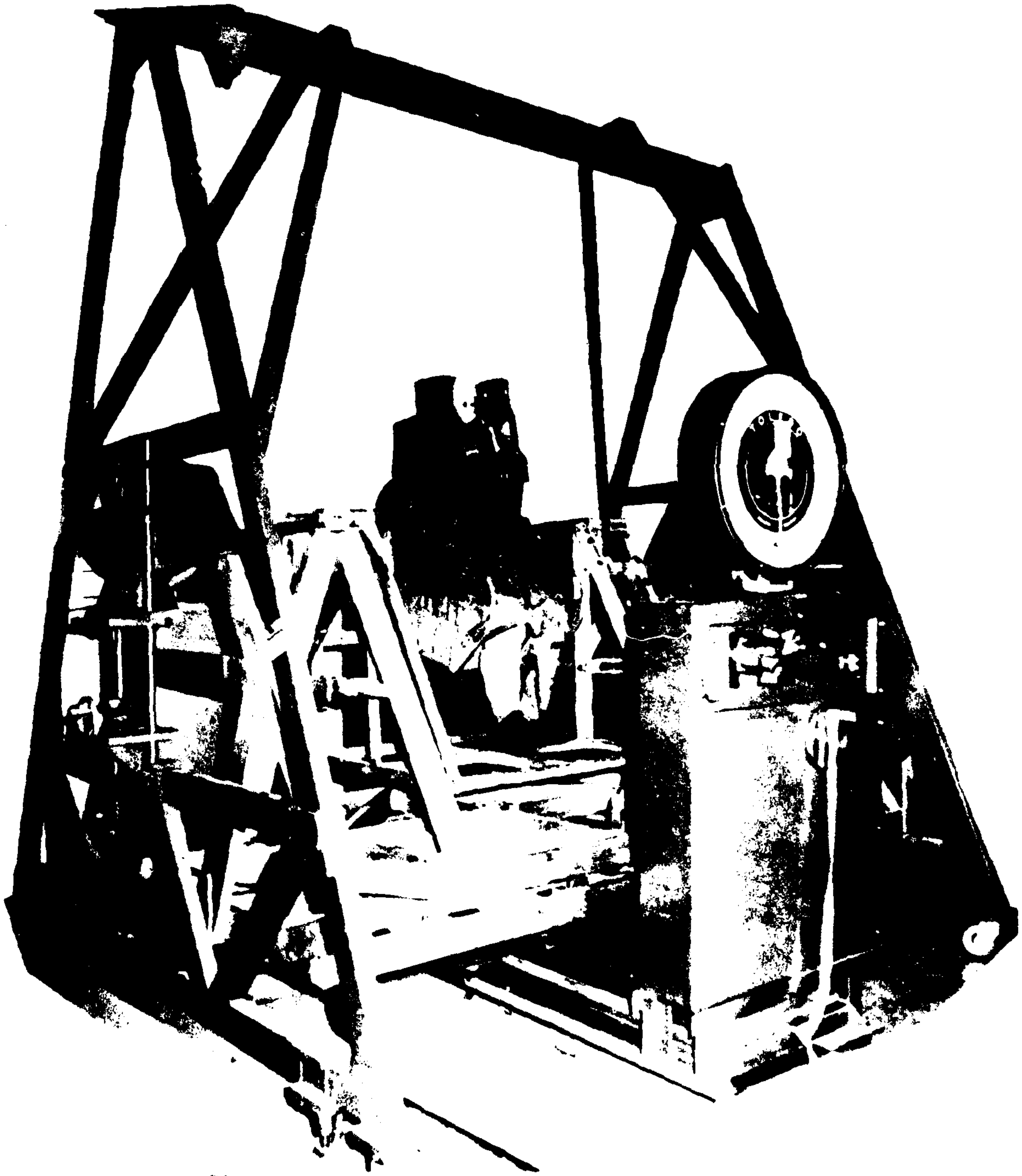


Figure 6. Center of Gravity/Inertia Meter

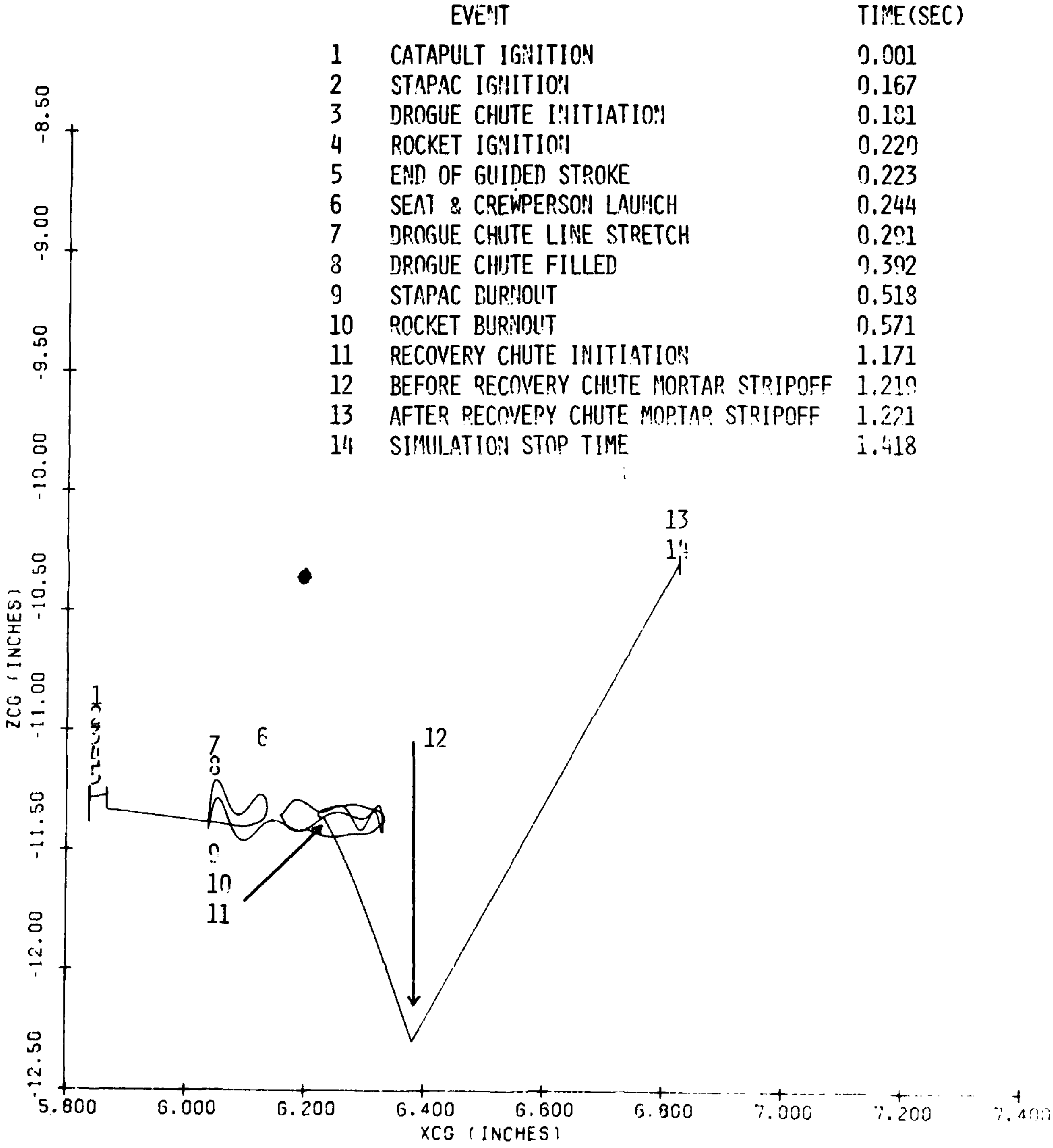


Figure 7. ZCG vs XCG SAFEST 49E-J1F

	EVENT	TIME(SEC)
1	CATAPULT IGNITION	0.001
2	STAPAC IGNITION	0.167
3	DROGUE CHUTE INITIATION	0.181
4	ROCKET IGNITION	0.220
5	END OF GUIDED STROKE	0.223
6	SEAT & CREWPERSON LAUNCH	0.244
7	DROGUE CHUTE LINE STRETCH	0.291
8	DROGUE CHUTE FILLED	0.392
9	STAPAC BURNOUT	0.518
10	ROCKET BURNOUT	0.571
11	RECOVERY CHUTE INITIATION	1.171
12	BEFORE RECOVERY CHUTE MORTAR STRIPOFF	1.219
13	AFTER RECOVERY CHUTE MORTAR STRIPOFF	1.221
14	SIMULATION STOP TIME	1.418

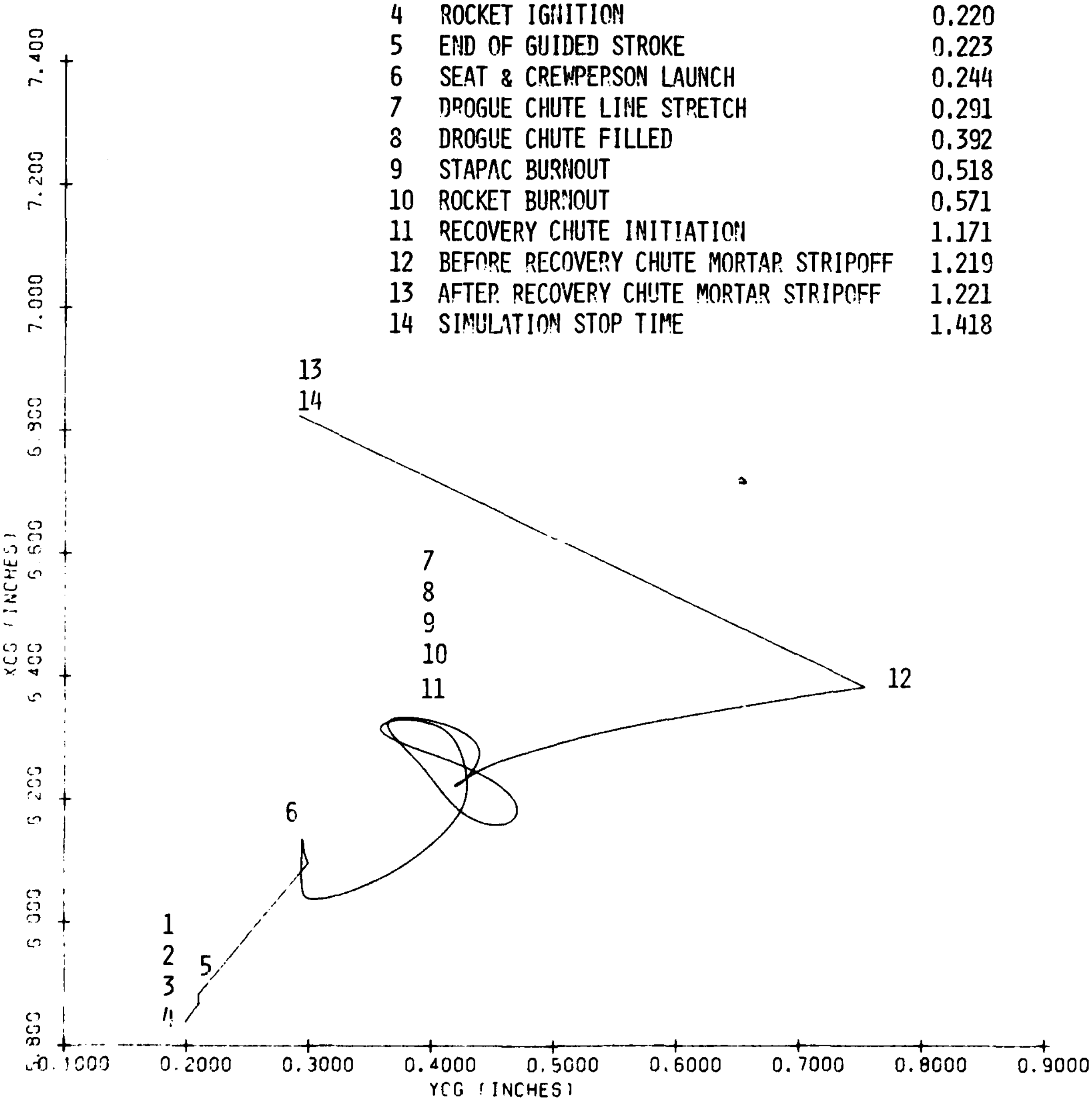


Figure 8. XCG vs YCG SAFEST 49E-J1F

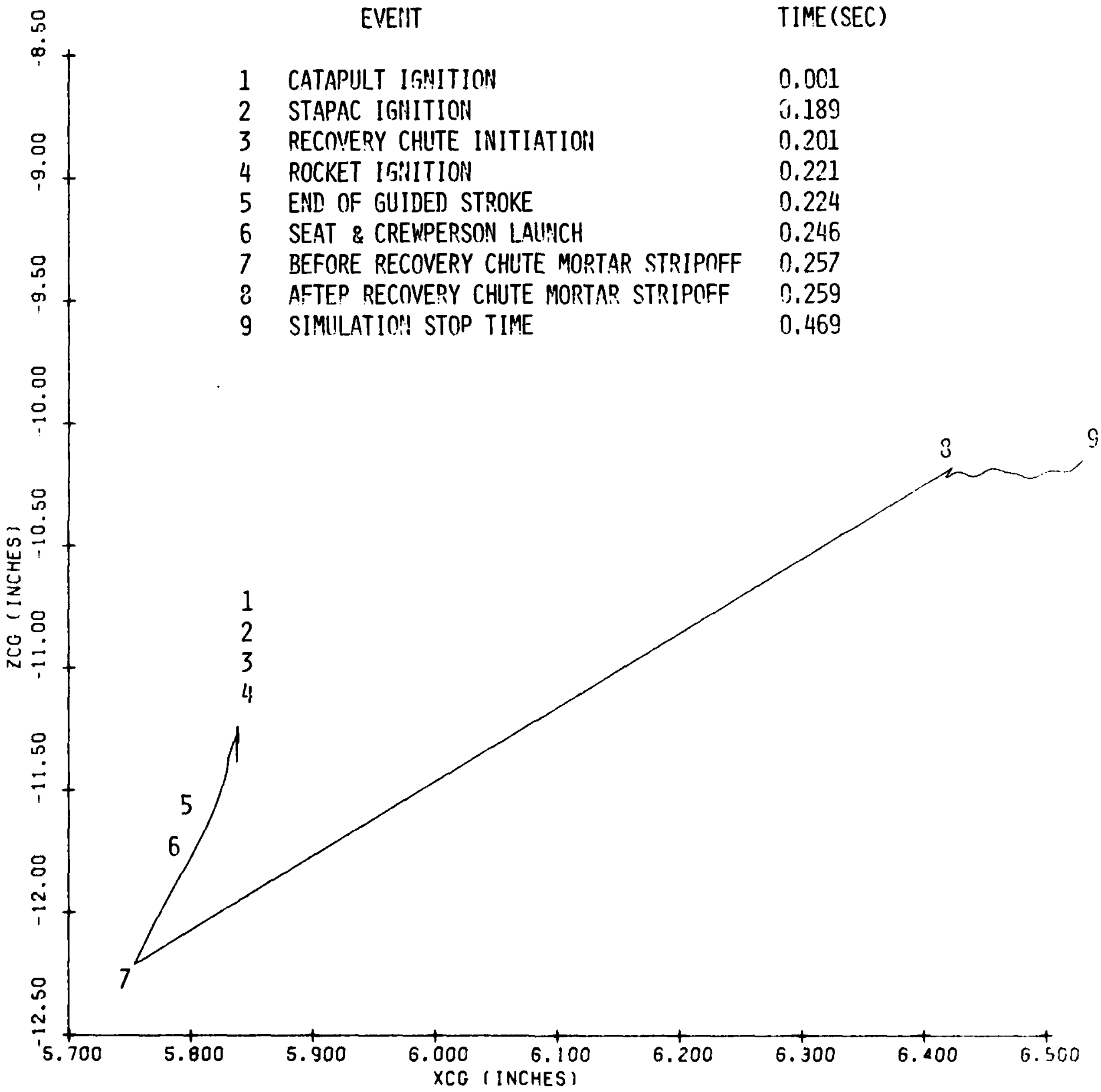


Figure 9. ZCG vs XCG SAFEST 49E-11A

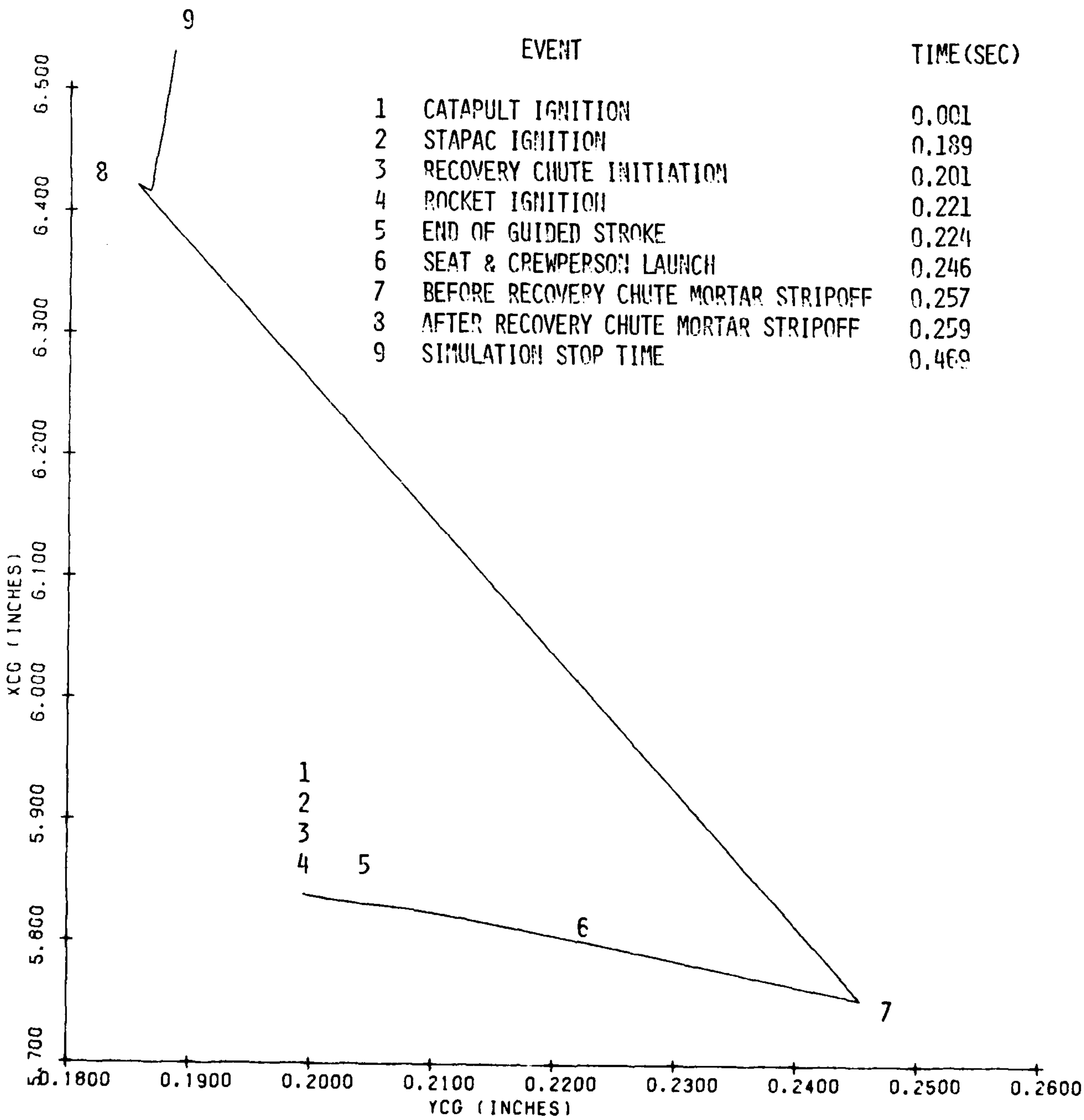


Figure 10. XCG vs YCG SAFEST 49E-IIA

SECTION IV

CORRELATION RESULTS

1. HIGH-SPEED-CASE 49E-J1F

Figures 11 through 34 present for comparison the empirically measured and computer predicted three-dimensional body axis accelerations, angular rates, catapult pressure, DRI and earth axis trajectory displacements for the high-speed 445 KEAS HITECH 49E-J1F and the low-speed 165 KEAS HITECH 49E-I1A tests.

For the high-speed case, Figures 11, 12, and 13 exhibit the acceleration profiles of the seat and crewperson in each axis. The computer simulated accelerations display reasonable correlation with the empirical data. Successful correlation of the computed accelerations with empirical data is confirmed by Figure 18 showing a comparison of DRI values.

For the high speed case, reasonable correlation exhibiting both order of magnitude and trend behavior for angular rates of the seat and crewperson combination is shown by Figures 14, 15, and 16. Additionally the computed catapult pressure shows correlation with measured pressures for the high-speed case (see Figure 17).

Earth axis downrange distance vs. time, lateral distance vs. time, altitude vs. time, and altitude vs. down range distance for the seat and crewperson combination are shown in Figures 19, 20, 21, and 22 respectively, for the high-speed case. The comparison between computed values and empirical data shows good correlation for the drogue chute deployment with the simulated drogue chute full open condition occurring 0.392 second after time of catapult (TOC) ignition, or correspondingly, 315.76 feet downrange from the point of TOC. From the empirical data summary contained in Table 2, the drogue chute full open condition occurred at 0.385 second after TOC. The occurrence of the computer simulated drogue chute line stretch and inflation process at a later time than the actual occurrence

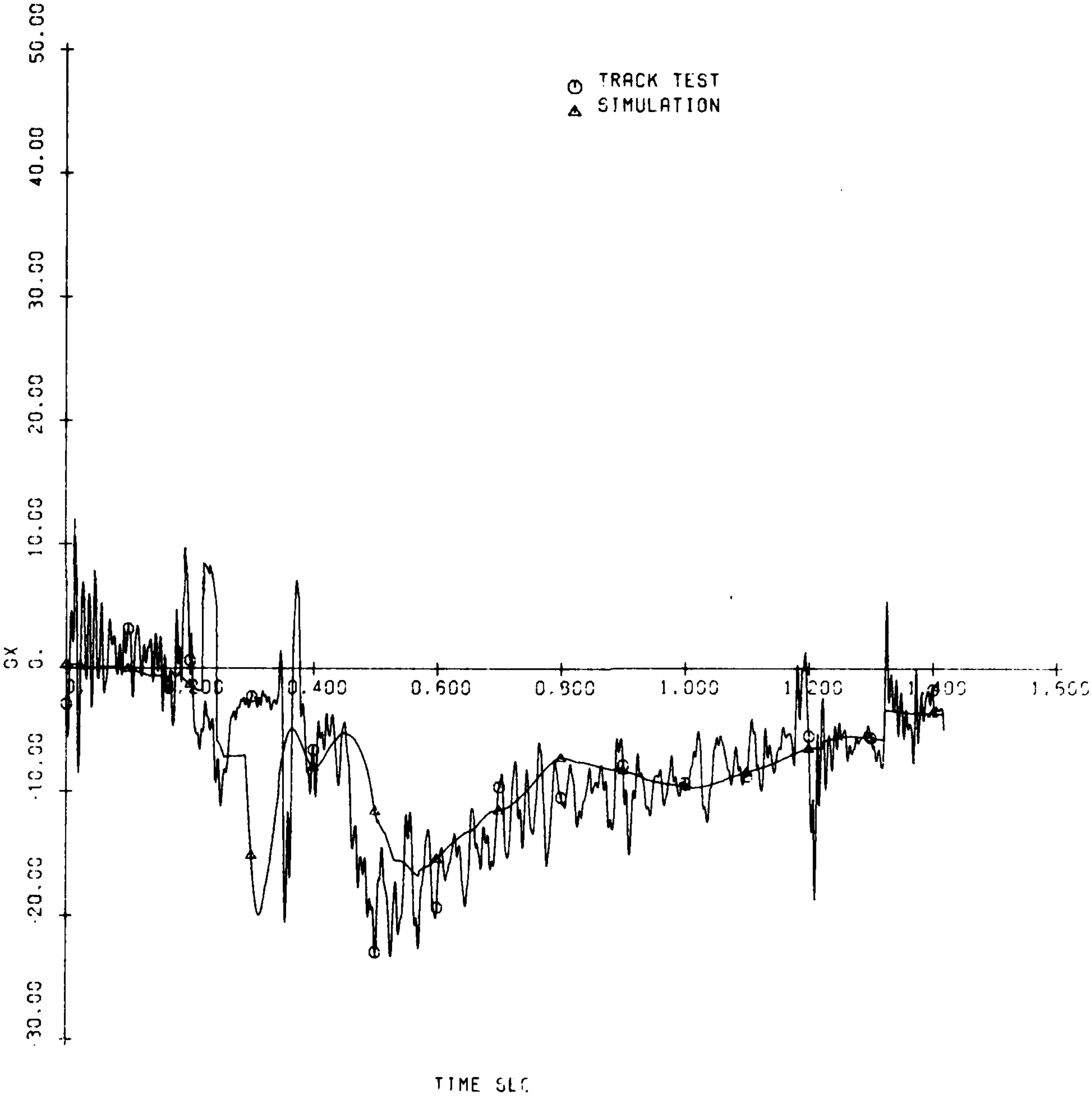


Figure 11. GX vs TIME 49E-J1F

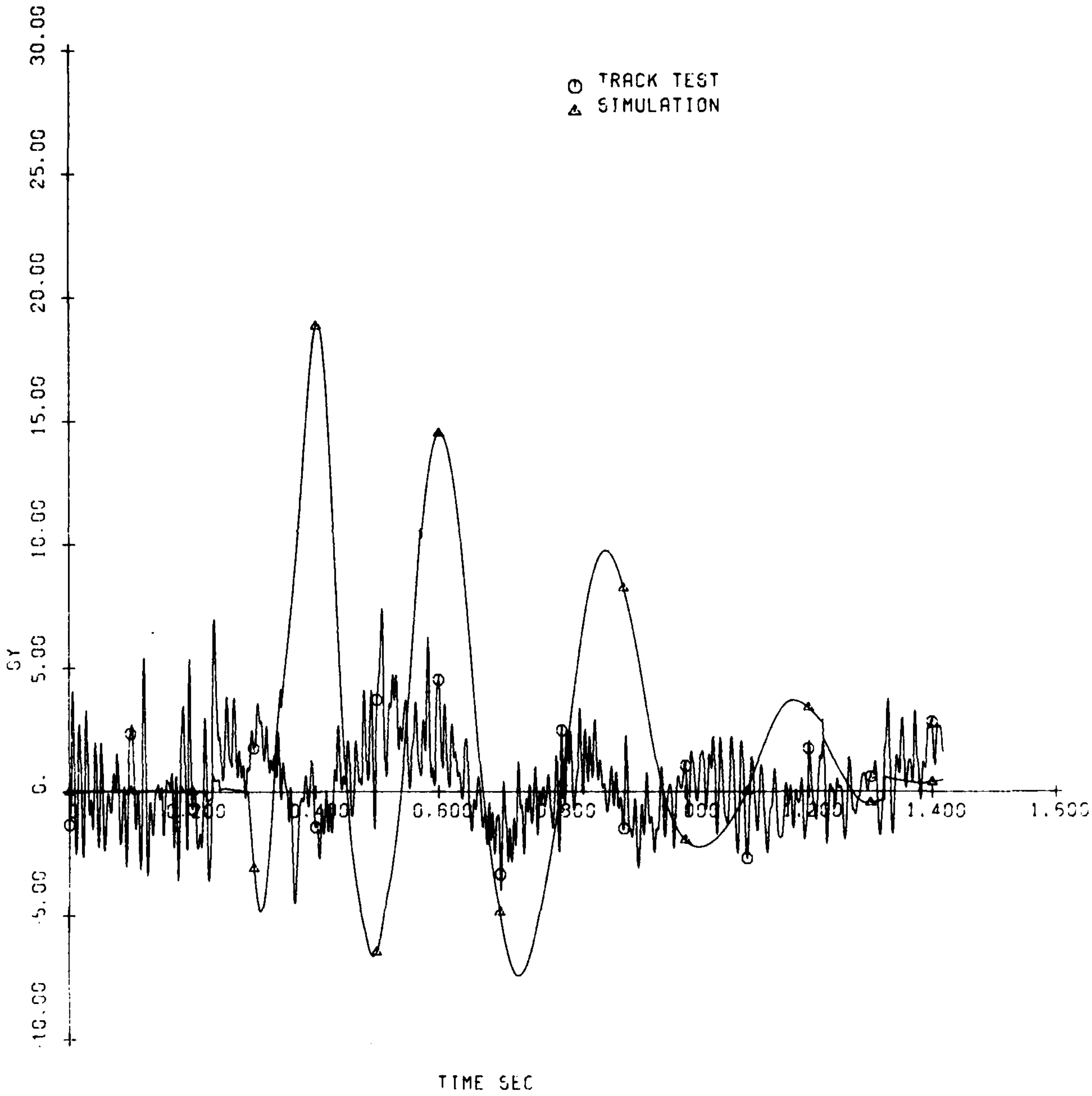


Figure 12. GY vs TIME 49E-J1F

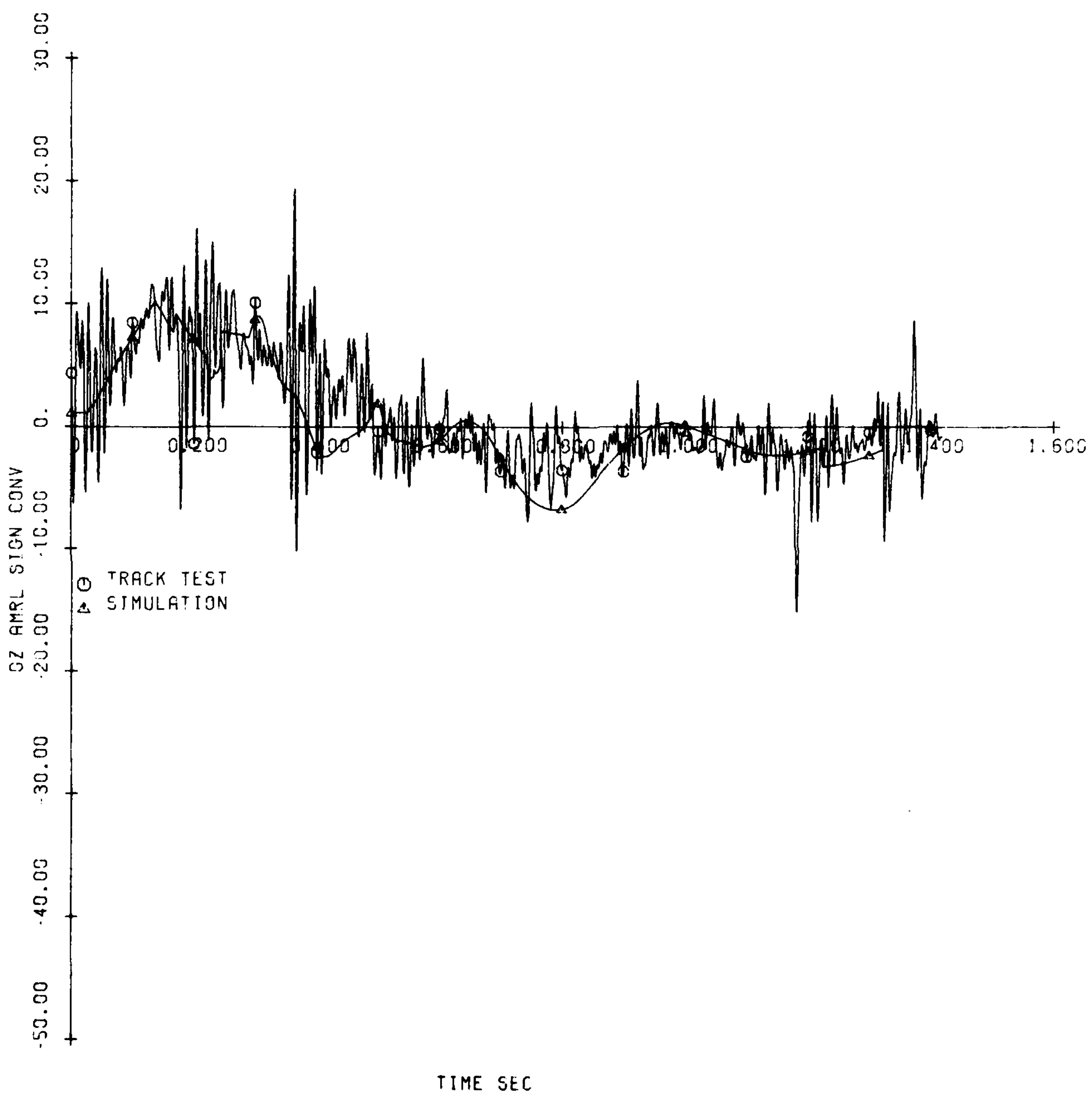


Figure 13. GZ vs TIME 49E-J1F

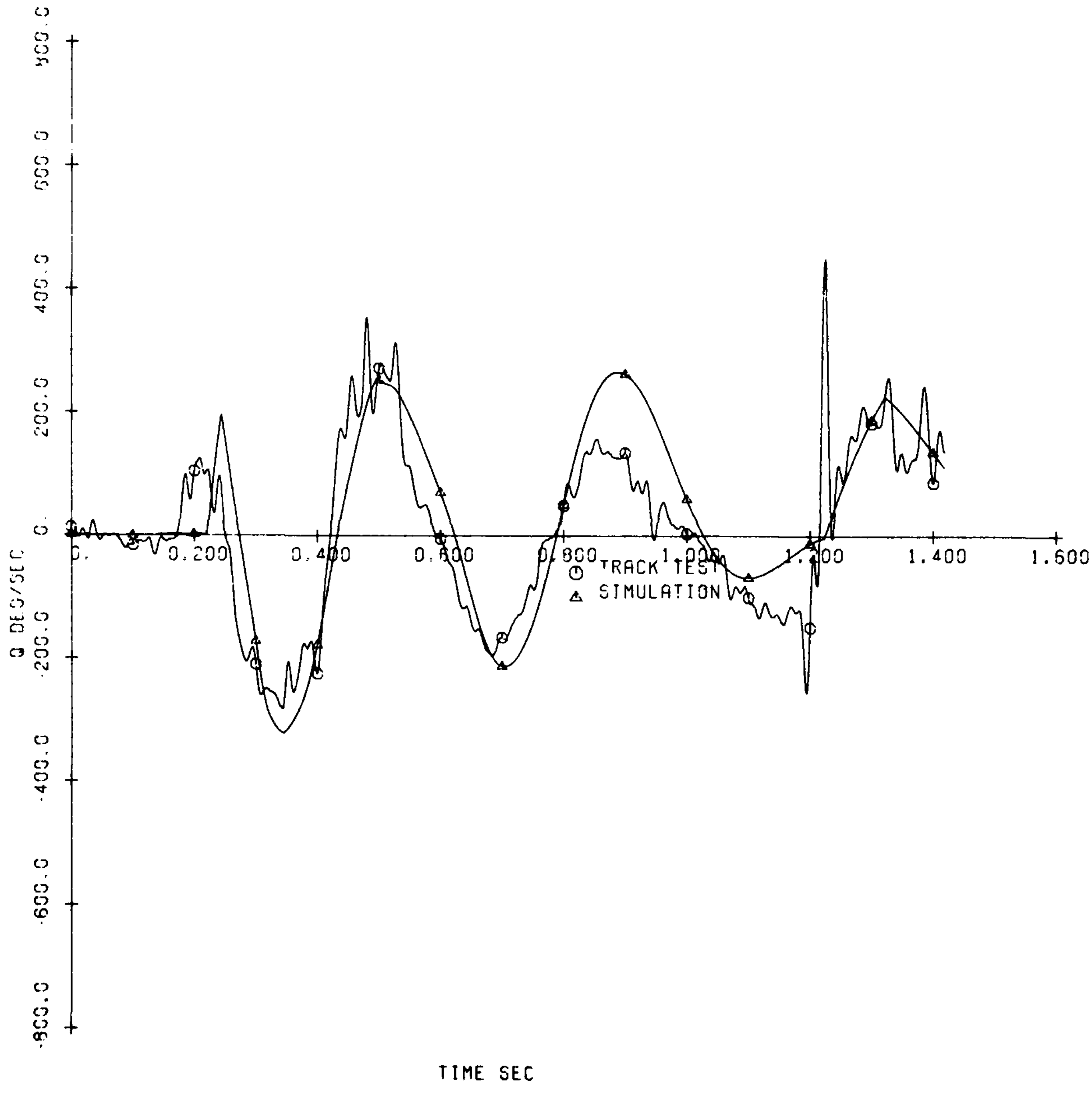


Figure 14. Q vs TIME 49E-J1F

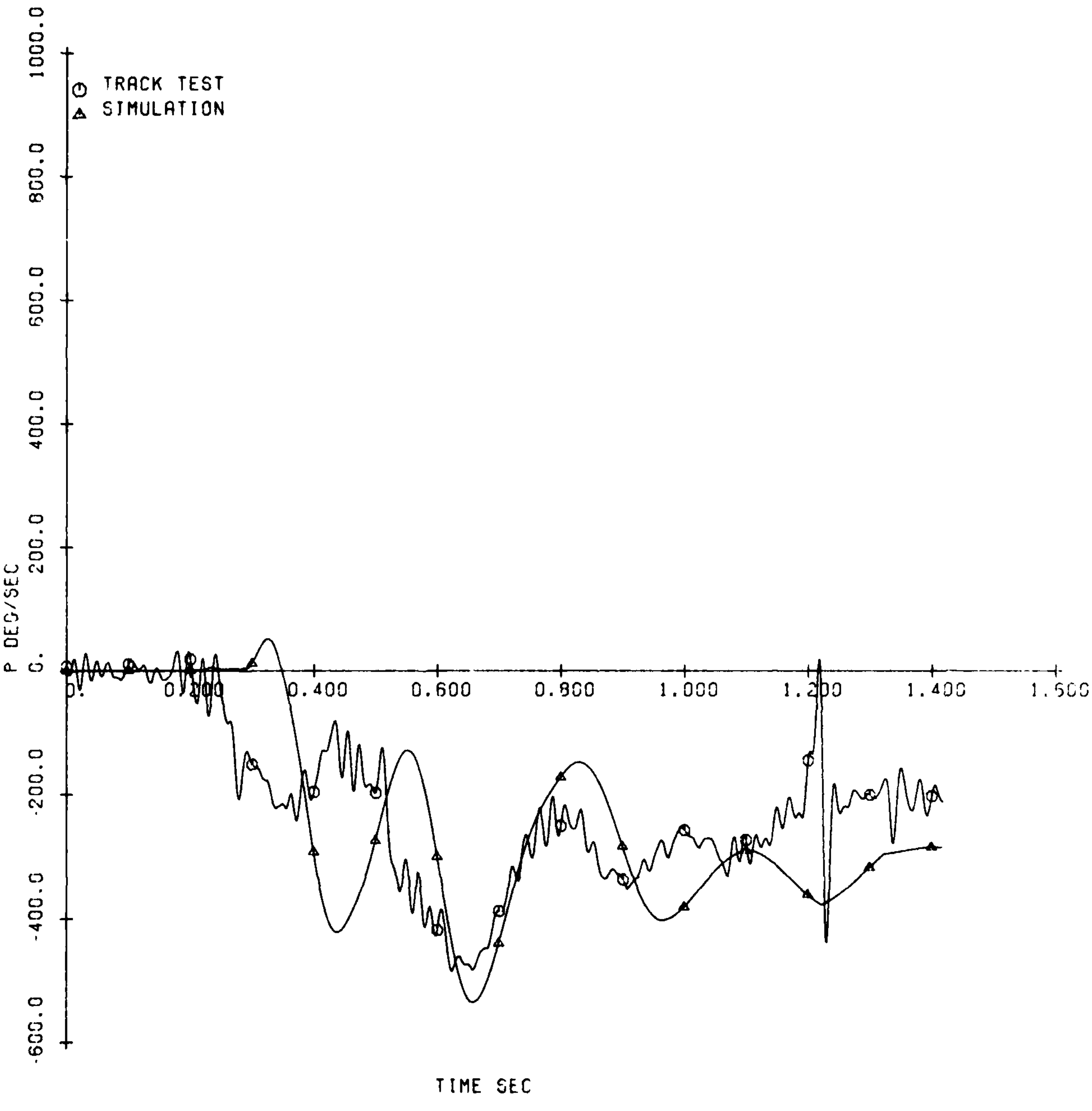


Figure 15. P vs TIME 49E-J1F

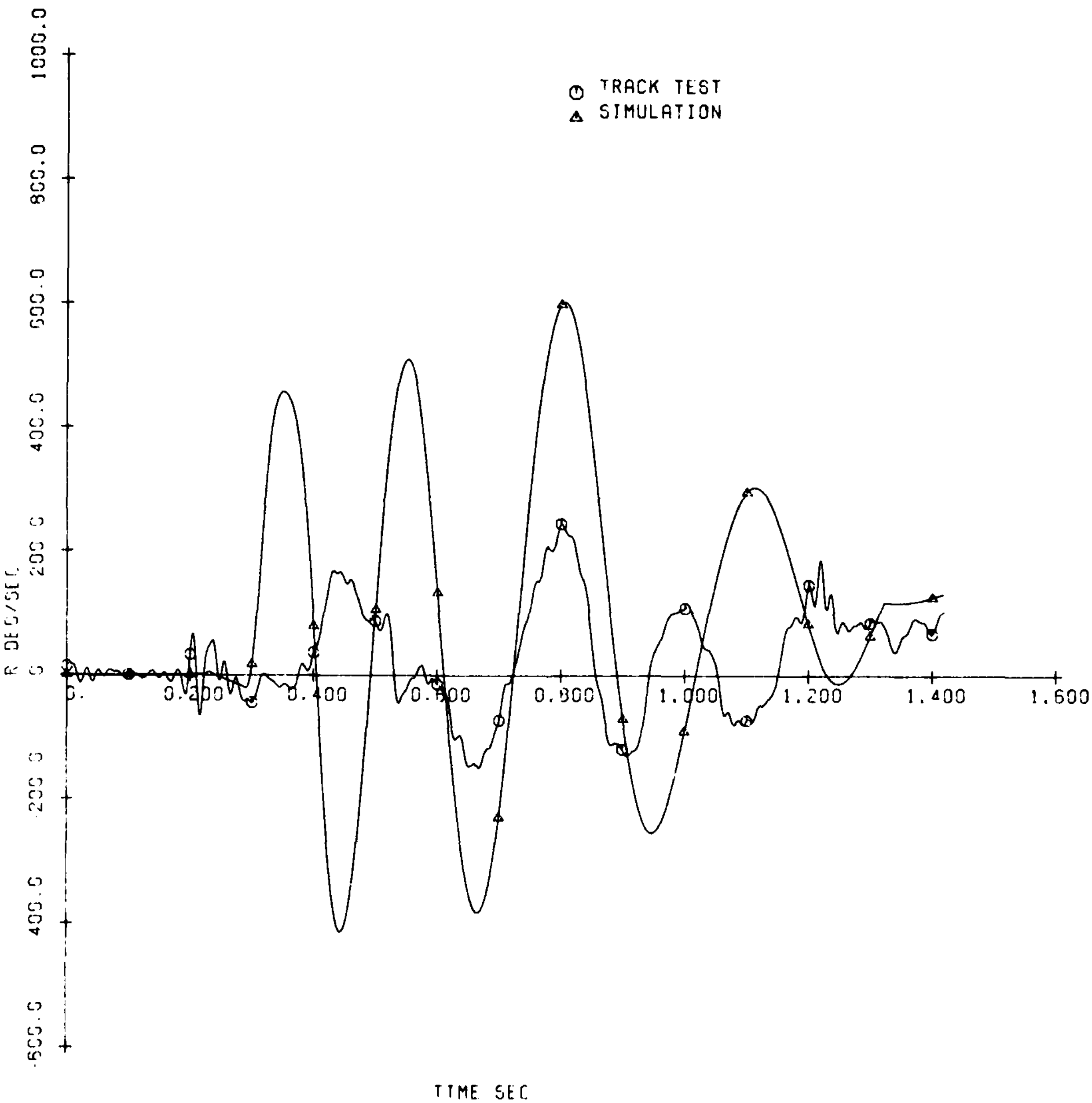


Figure 16. R vs TIME 49E-J1F

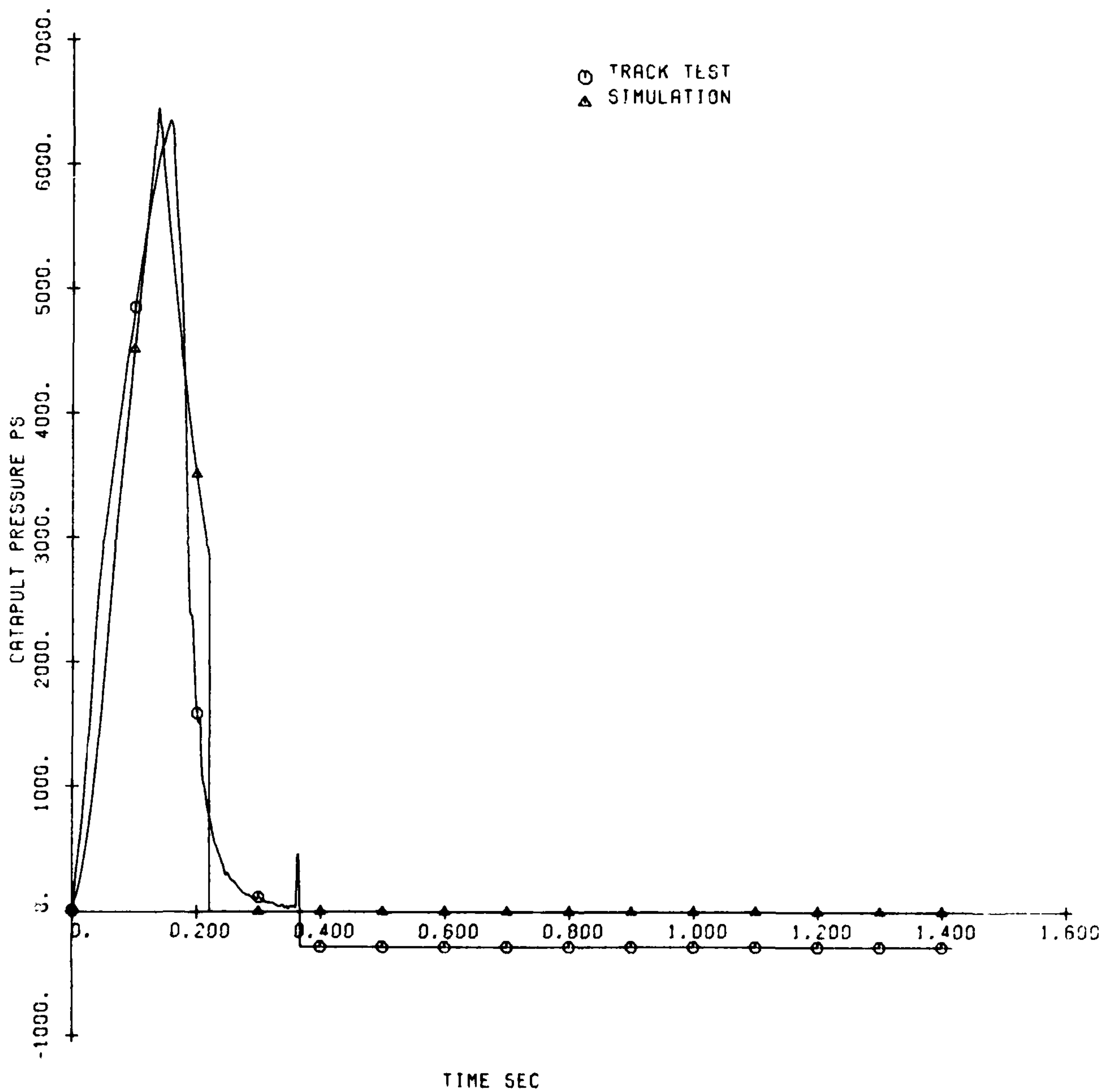


Figure 17. CATAPULT PRESSURE VS TIME 49E-J1F

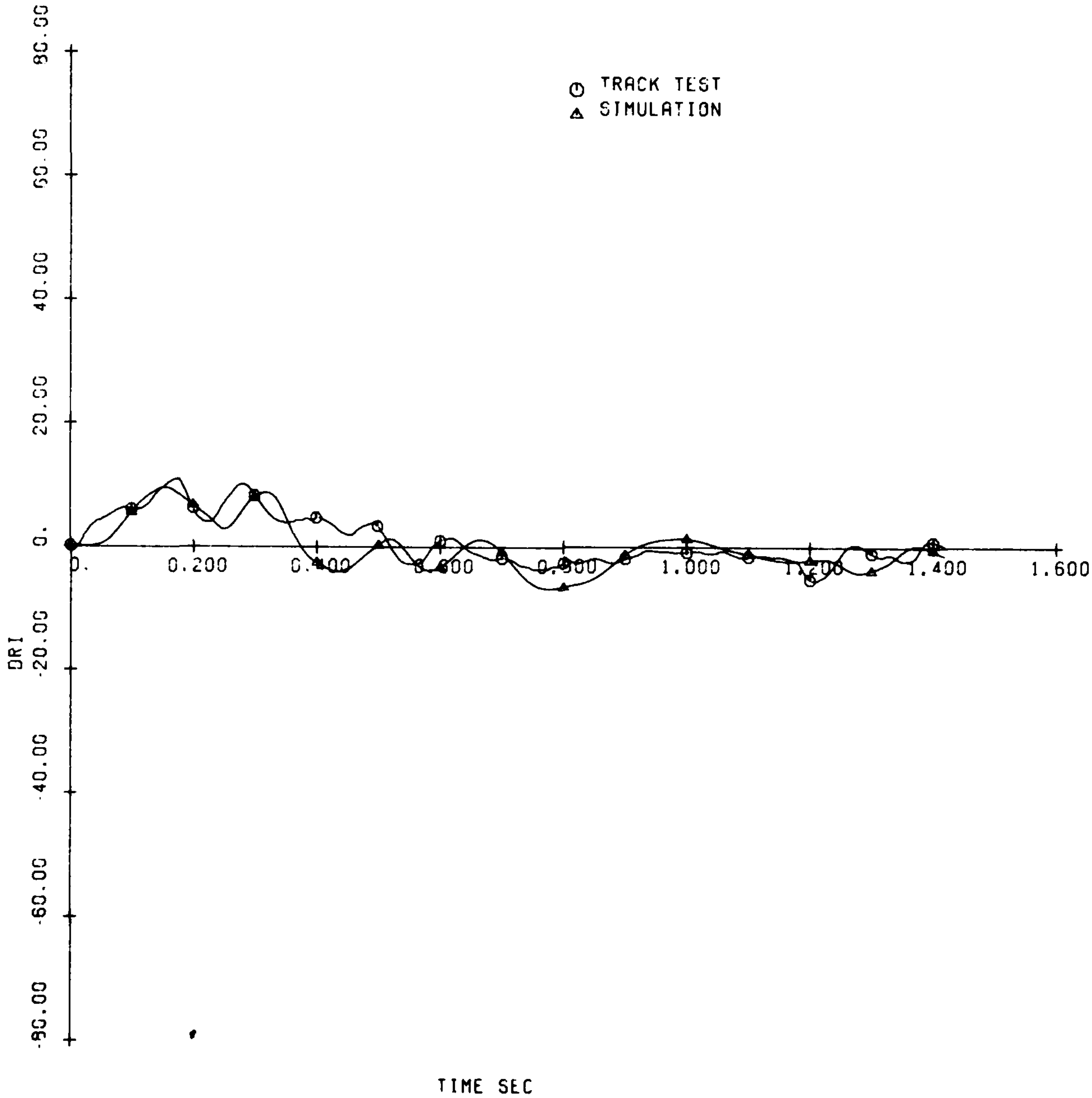


Figure 18. DRI vs TIME 49E-J1F

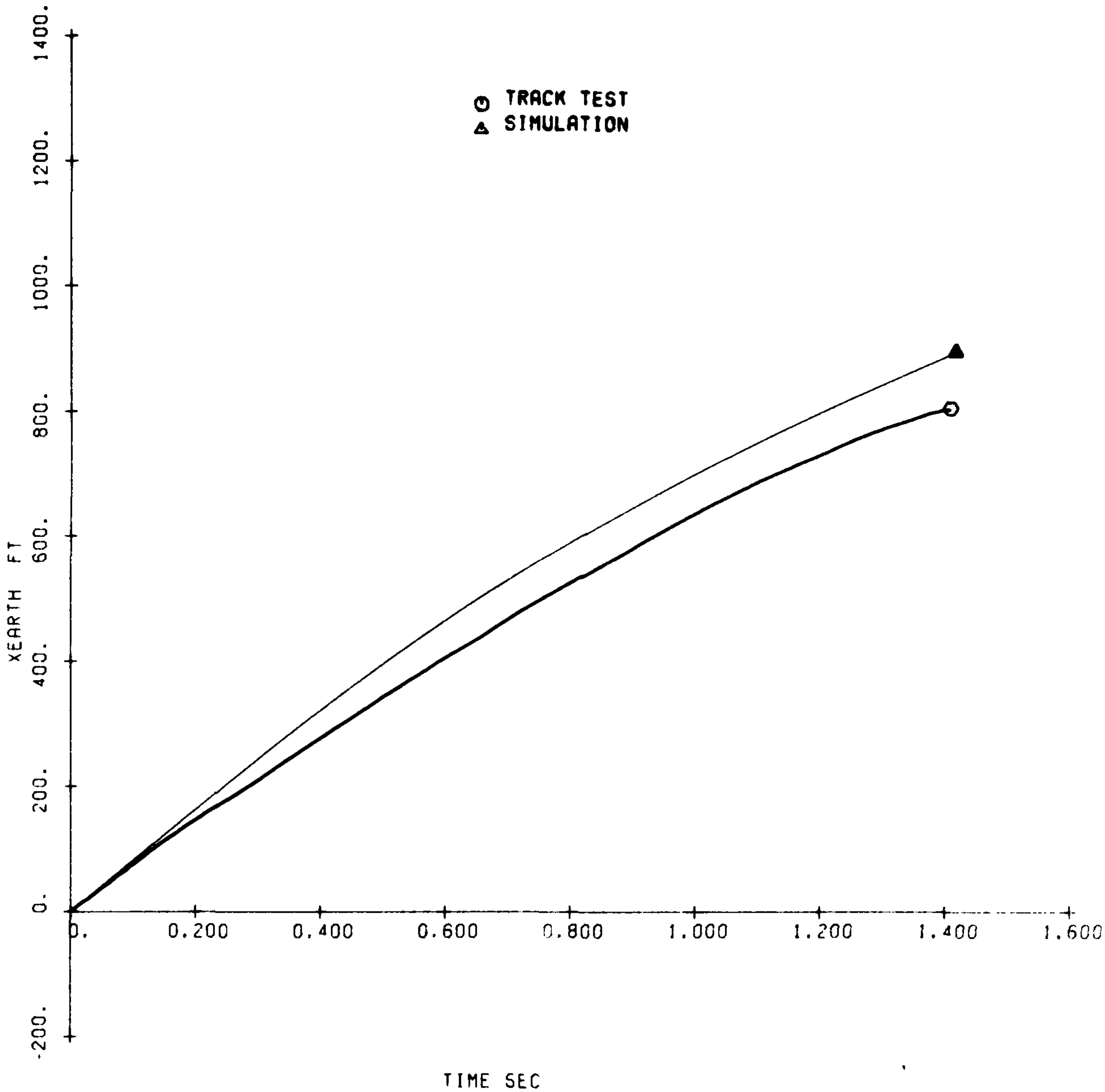


Figure 19. XEARTH vs TIME 49E-J1F

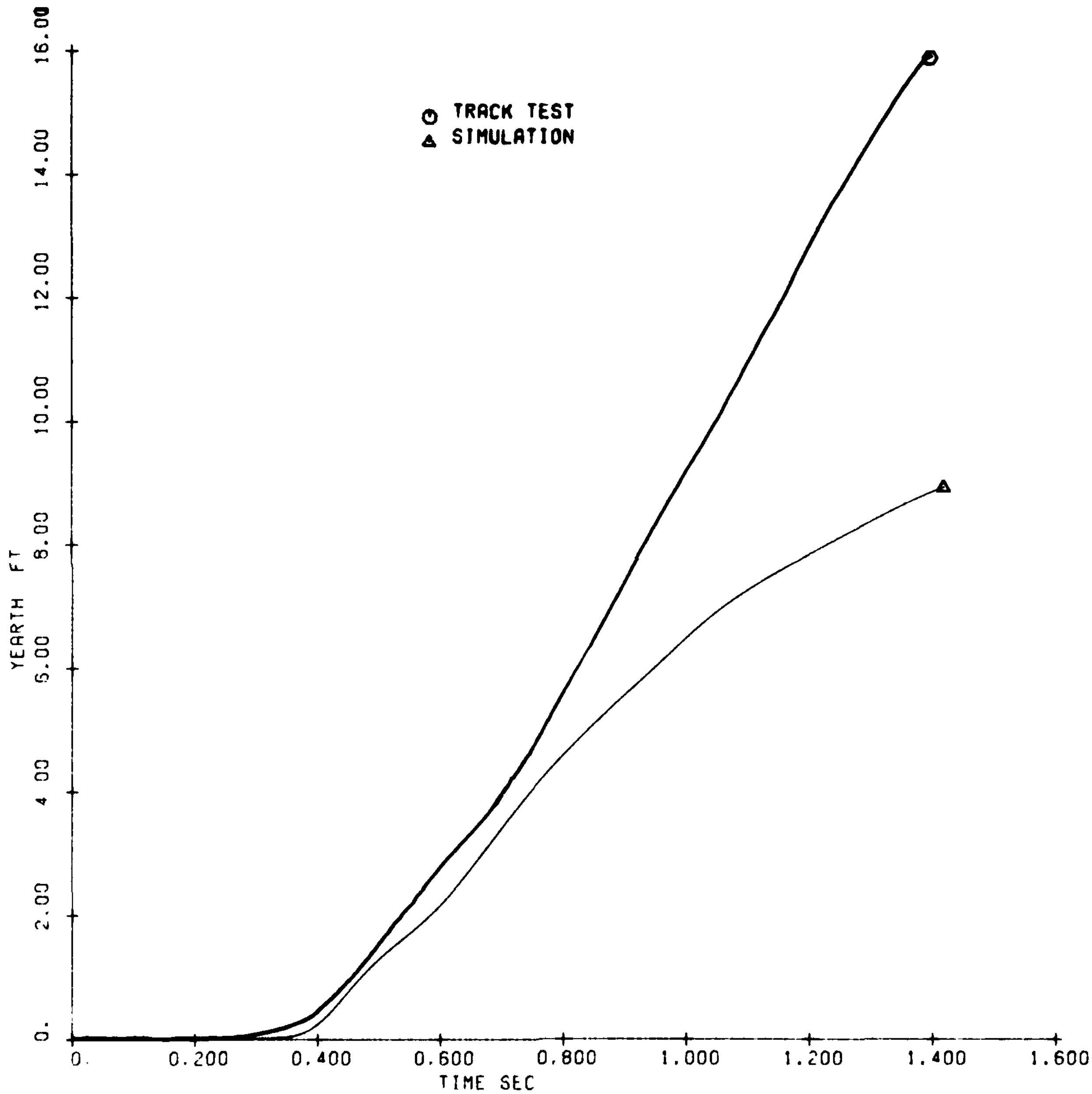


Figure 20. YEARTH vs TIME 49E-J1F

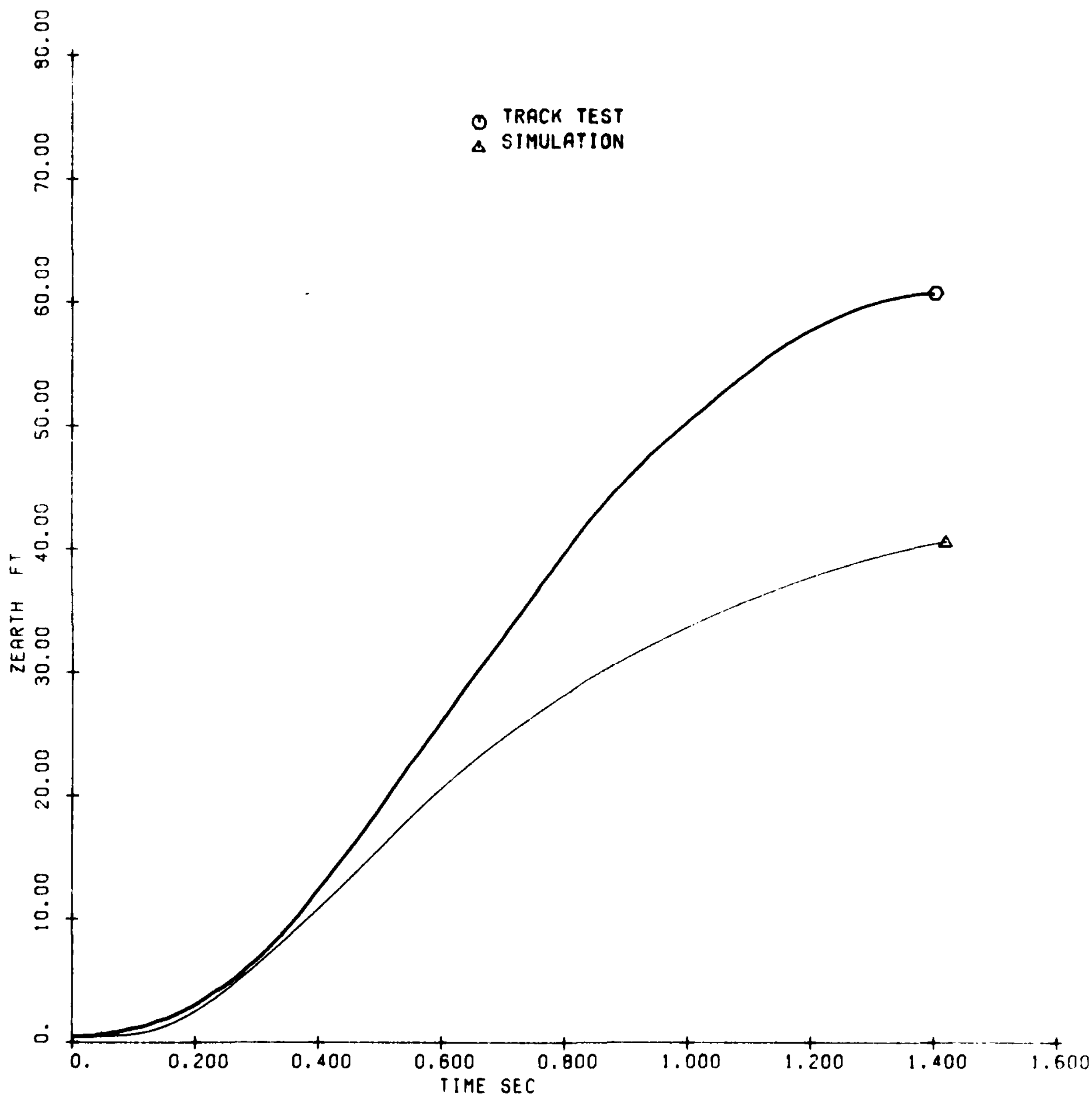


Figure 21. ZEARTH vs TIME 49E-J1F

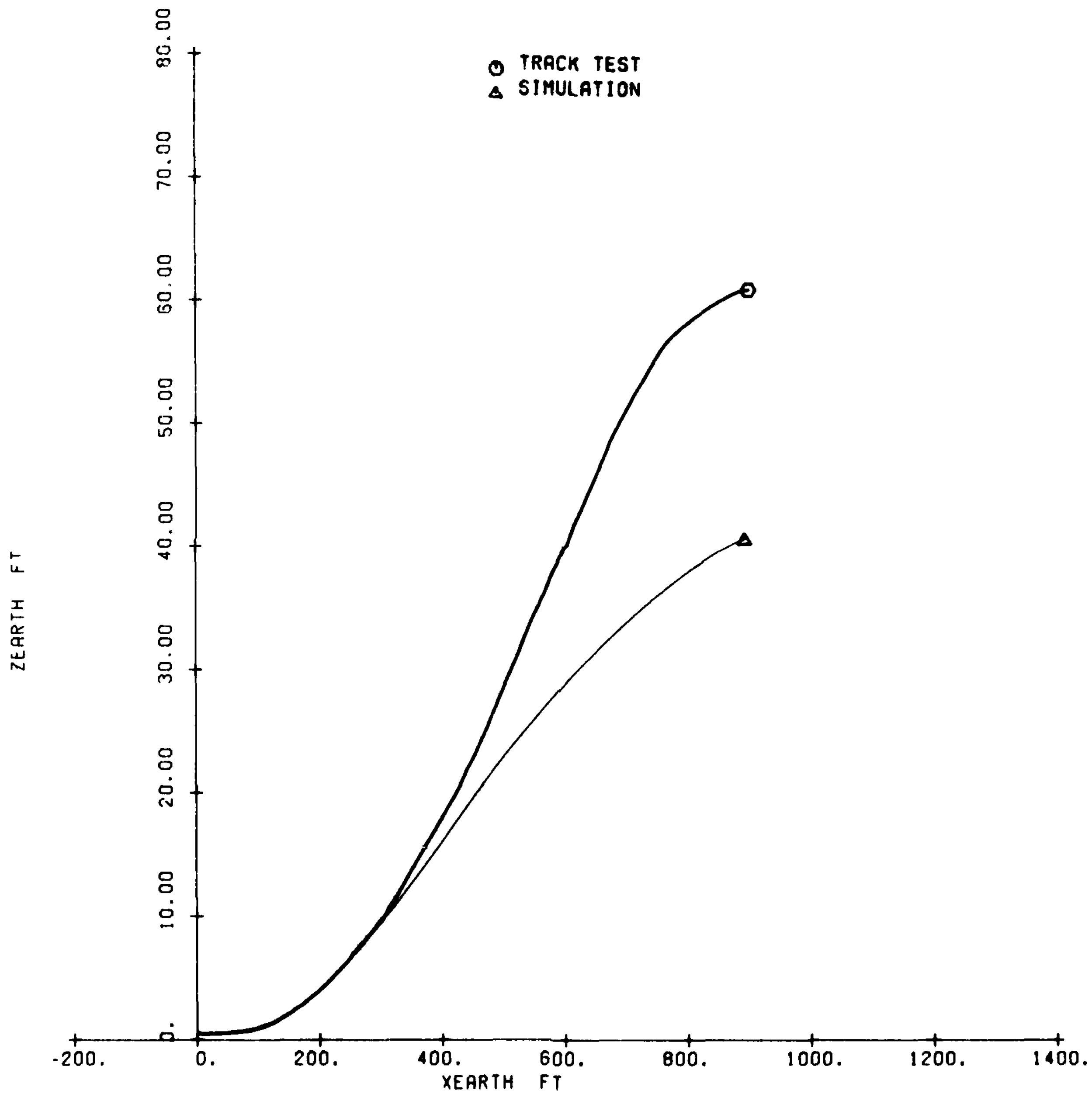


Figure 22. ZEARTH vs XEARTH 49E-J1F

of the events would be expected to result in a simulated trajectory exhibiting slightly higher altitude for a given downrange distance thereafter. However, the results shown in Figure 13 indicate the opposite. The trajectory performance degradation occurring after the drogue chute inflation process is complete necessitates future improvements to the mathematical models.

2. LOW-SPEED-CASE 49E-I1A

For the low-speed 165 KEAS case, Figures 23, 24, and 25 exhibit the correlation between empirical and computed accelerations along the body-axis of the seat and crewperson combination. The computer simulation acceleration preliminary results predict the magnitude and trends of the accelerations recorded during the 49E-I1A track test.

Figures 26, 27, and 28 represent the correlation for the angular rates measured during the track test and those computed by SAFEST. Differences in the trends between the empirical data and the analytical data are attributed to specific input data values for which estimates were rationalized. For low-speed simulations, the aerodynamic forces on the ejecting seat and crewperson are small during the guide rail constrained phase of ejection.

Figure 26 shows that with small or negligible aerodynamic force on the emerging seat and crewperson during ejection, the catapult produces a moment which pitches the seat forward in a negative direction through a distance allowed by mechanical tolerance specifications and bending of the guide rails as revealed by the empirical data in Figure 26. Although the SAFEST computer model considers rail flexure as a result of aerodynamic and non-aerodynamic forces upon the seat and crewperson, the input data available for the rail rigidity matrix generates too much stiffness in the rails for the low-speed test case simulation to accurately simulate the initial pitch rate. However, the trend of the pitch rate which develops after rocket ignition at 0.221 second, the change in the rate at 0.246 second corresponding to seat and crewperson launch from the rails, and the reversal of the rate from increasing values to decreasing values at 0.26 second which correlates to the recovery parachute mortar stripoff event, exhibits significant correlation comparisons. The empirical data reflects the above events occurring slightly sooner than the corresponding computer simulated event with the recovery parachute mortar stripoff event occurring at 0.246 second.

The large effect of the recovery parachute deployment on the seat and crewperson rates for the computer results was anticipated for the low speed case. The properties of the propellant used for input to the SAFEST program represents an estimate of propellant consumed vs web burned for the mortar device. The values utilized for input appear to generate too large of a mortar force which effects the computed pitch rate. Additionally the resulting behavior of the seat and crewperson motion about the center of gravity shows the computer simulation experiences a more pronounced response to the shift in c.g. upon the departure of the recovery chute pack when compared to the empirical data. However, the simulated pitch rate begins a return trend toward the empirical results prior to completion of correlation analysis.

Figures 27 and 28 show the ejection seat and crewperson combination computer-generated and empirically measured roll rates and yaw rates. As a result of the closely cross-coupled mass inertia of the ejection seat and crewperson combination, the correlation of the body axes roll rates and yaw rates was not achieved. However, the computer-generated roll and yaw rates are consistent with the predicted pitch rate of Figure 26. The cyclic behavior of the predicted pitch rate prevents the development of correlatable values of roll rate and yaw rate. Improved correlation between the predicted and empirical pitch rates, as previously discussed, should result in correlatable roll and yaw rates.

Correlation between the computer generated and empirically measured catapult pressures is shown in Figure 29. The track test data pressure time curve results in a slightly larger impulse applied to the ejection seat compared to the impulse available from the computer-generated pressure time curve. The computer-simulated performance of the catapult produces a peak pressure which is 6% below the maximum measured pressure obtained during the 49E-11A track test.

Figure 30 shows correlation of the computed dynamic response index (DRI) values determined from computer-generated body axes accelerations with the DRI values calculated from empirically measured body axes accelerations. The predicted correlation is consistent with the previously presented correlation of body axes accelerations (see Figures 23, 24, and 25). Earth axis position vs time is presented for each axis in Figures 31, 32, and 33. Additionally, altitude over downrange distance is displayed in Figure 34. The simulated trajectory performance (see Figures 33 and 34) is degraded by the pitch attitude resulting from discrepancies predicted for the pitch rate of the seat and crewperson combination after the recovery parachute mortar strip-off event and prior to the rocket burnout.

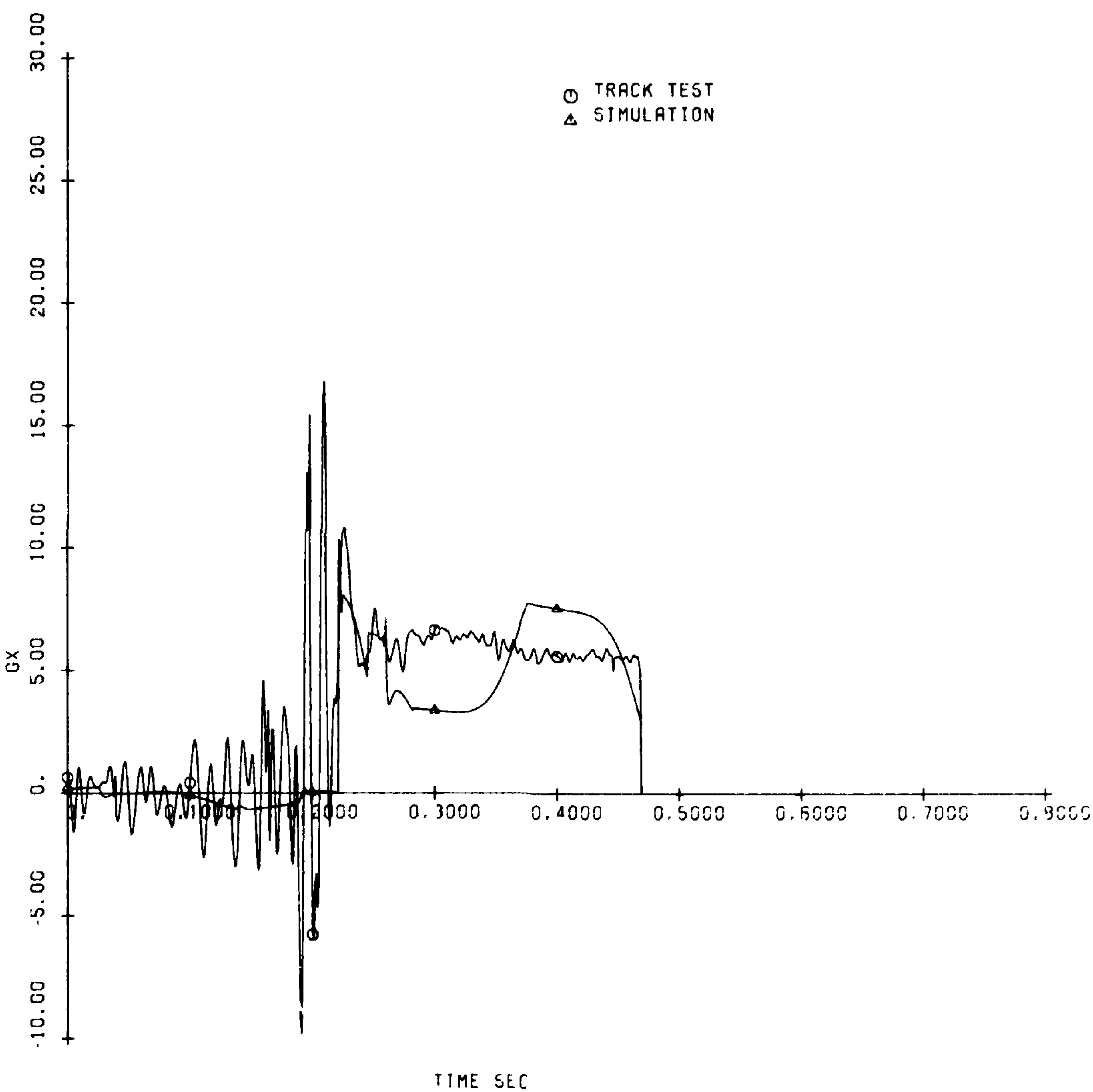


Figure 23. GX vs TIME 49E-I1A

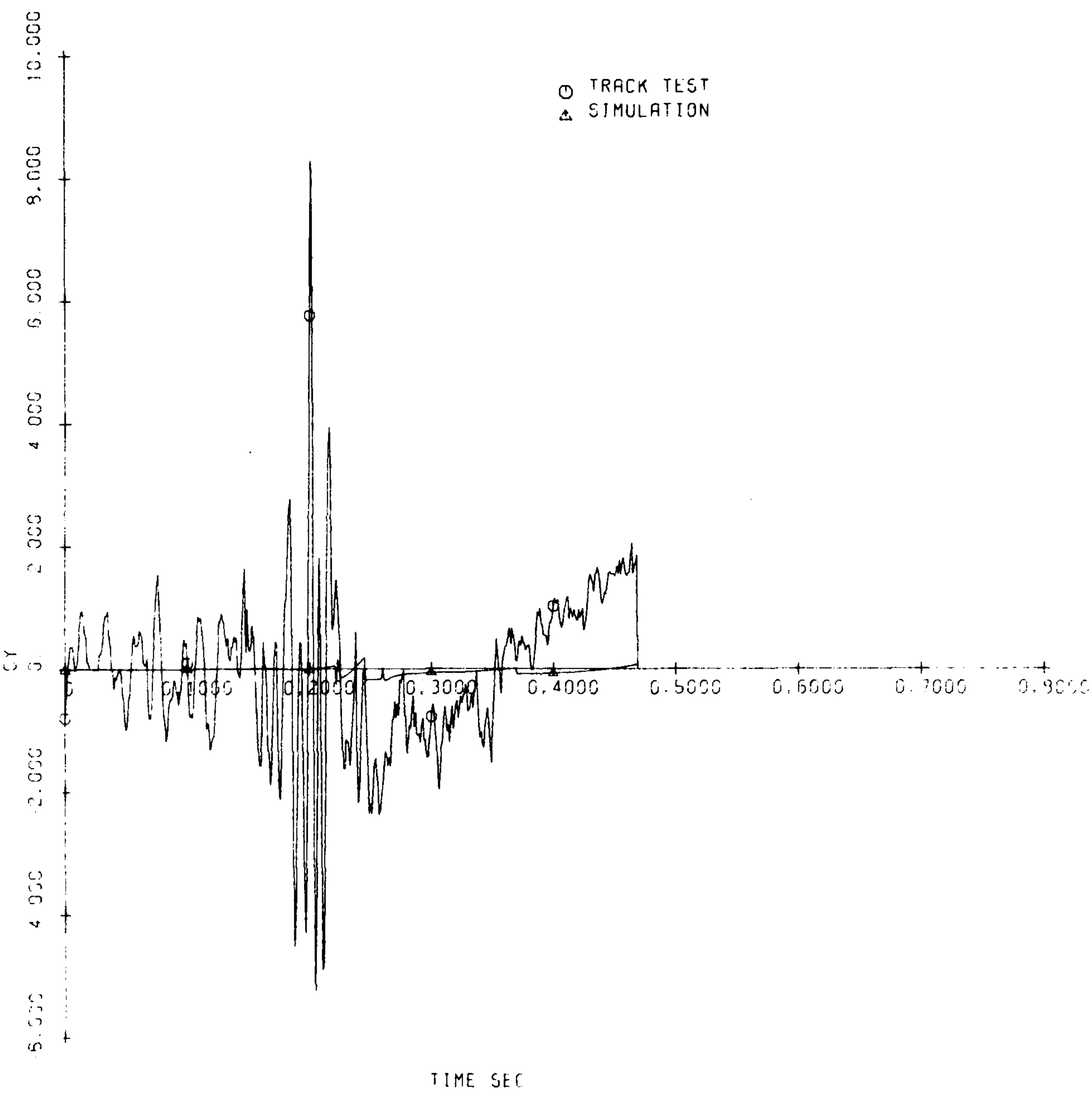


Figure 24. GY vs TIME 49E-I1A

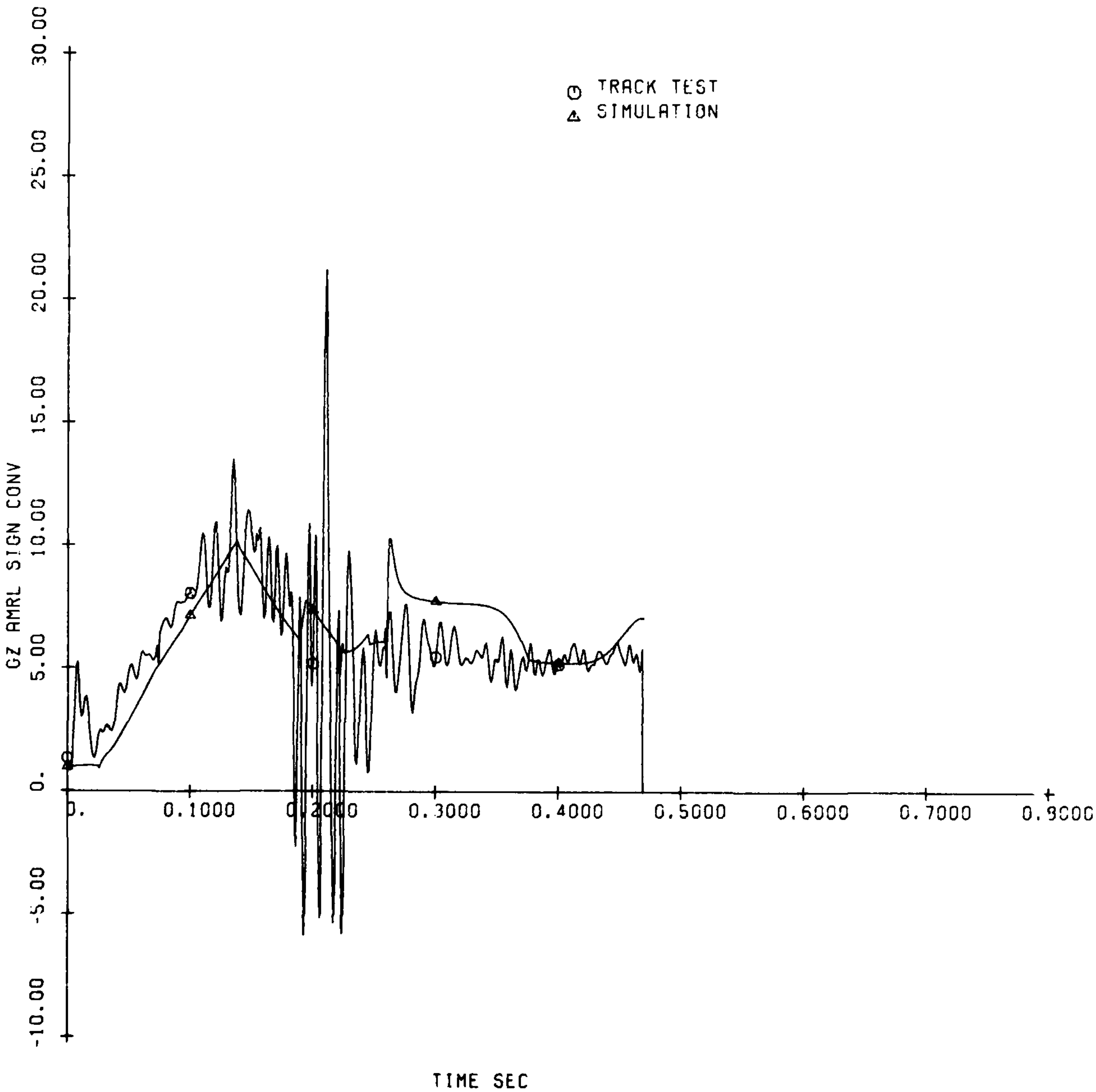


Figure 25. GZ vs TIME 49E-11A

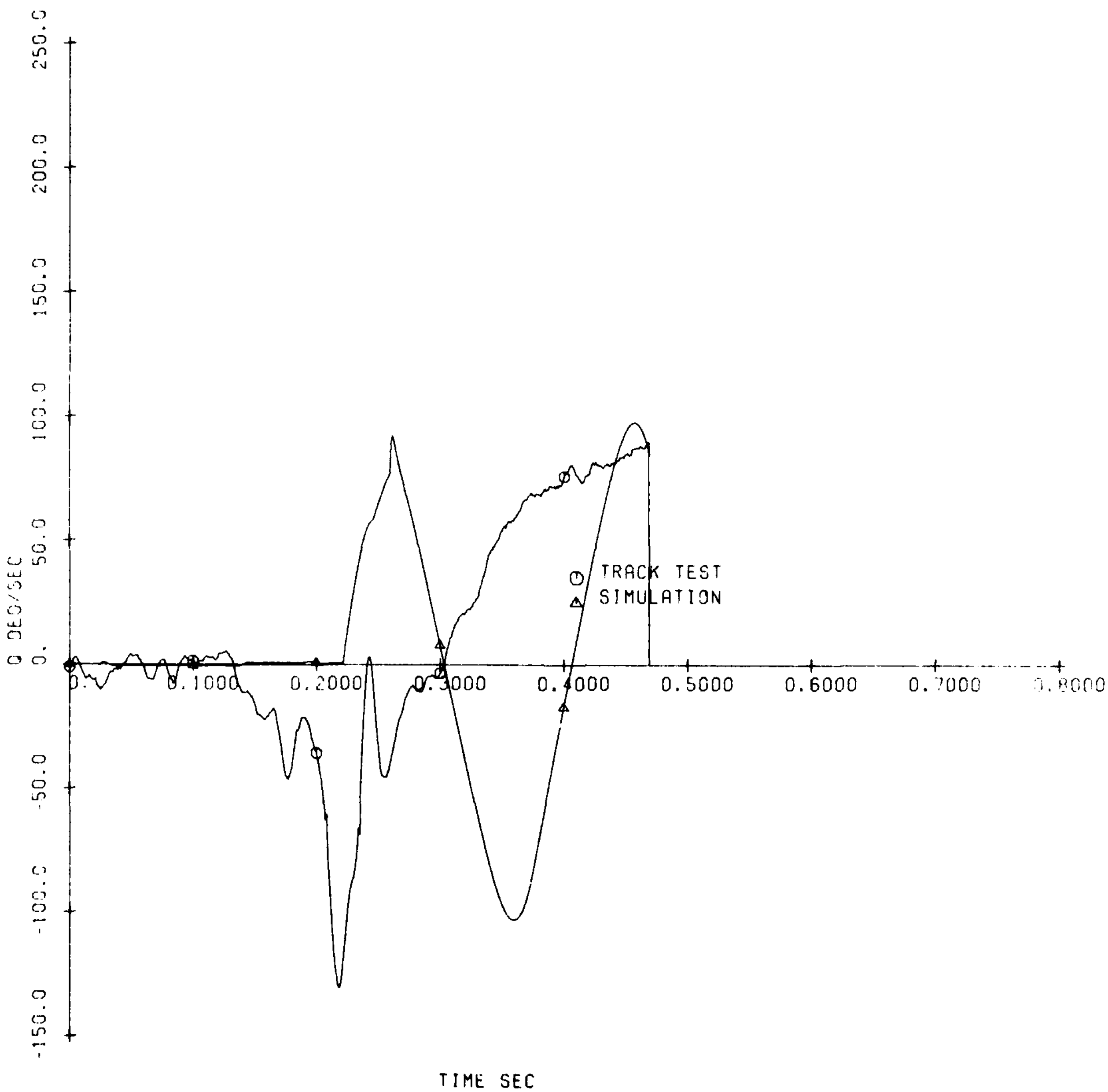


Figure 26. Q vs TIME 49E-11A

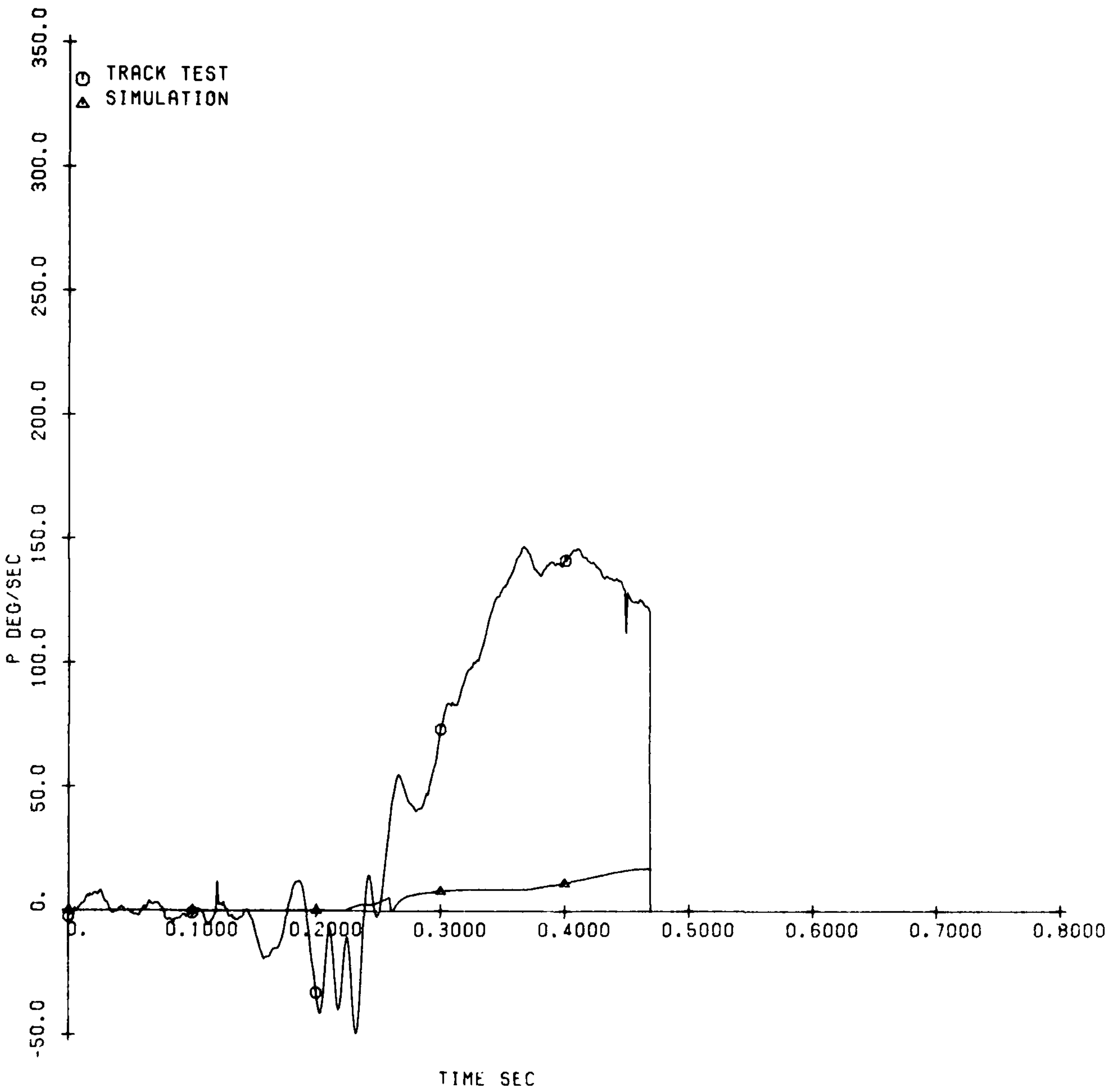


Figure 27. P vs TIME 49E-11A

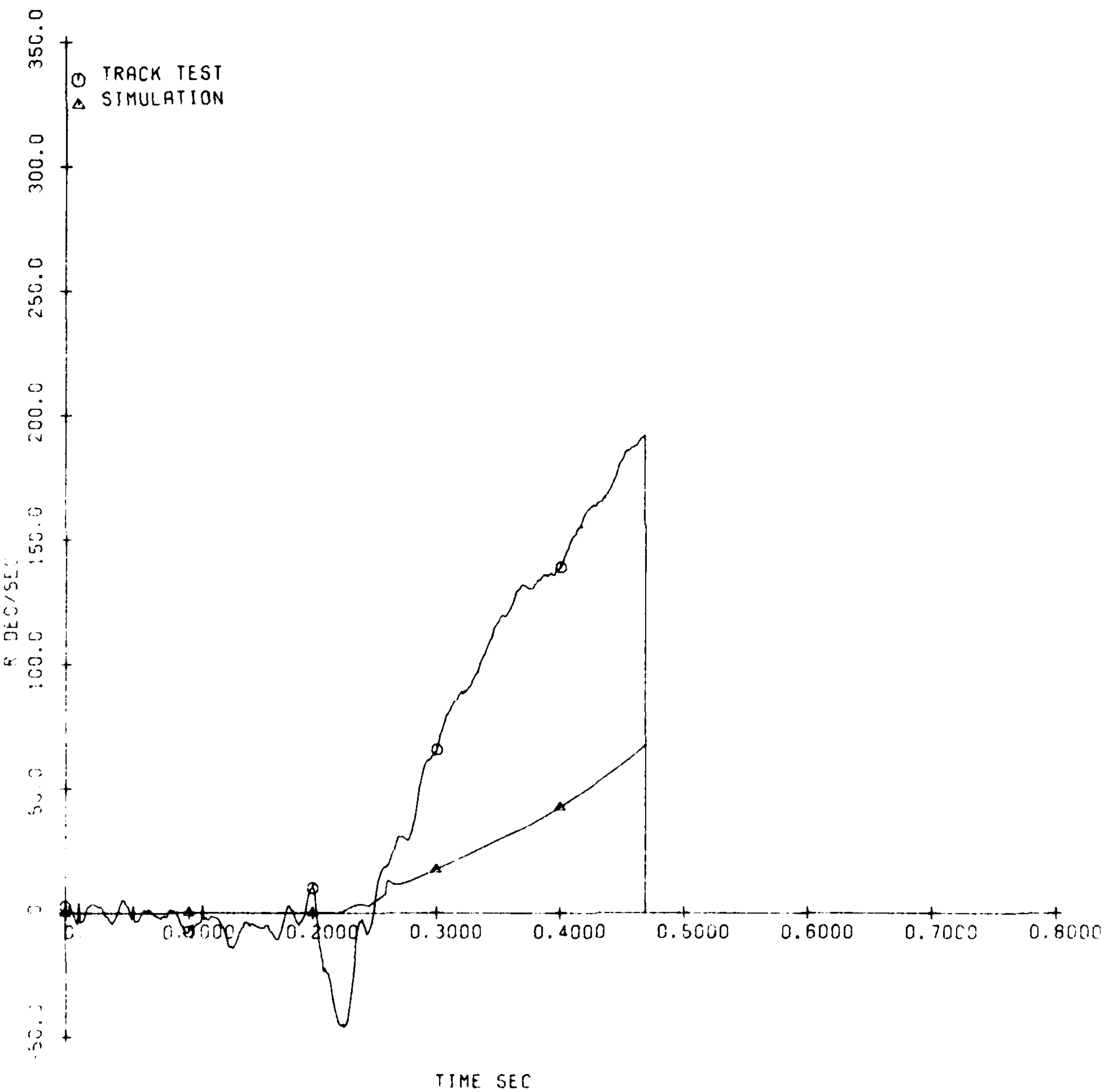


Figure 28. R vs TIME 49E-11A

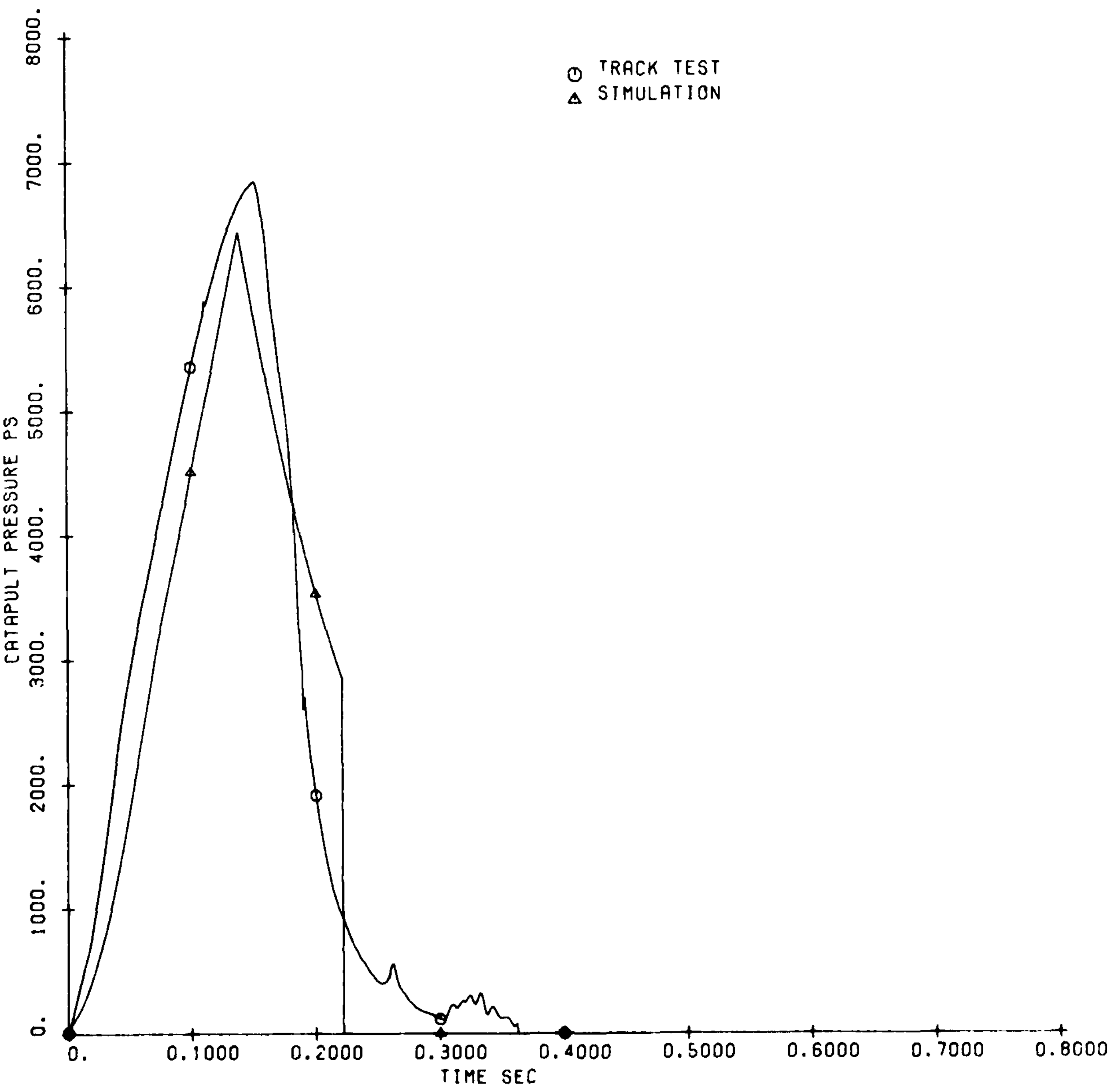


Figure 29. CATAPULT PRESSURE vs TIME 49E-11A

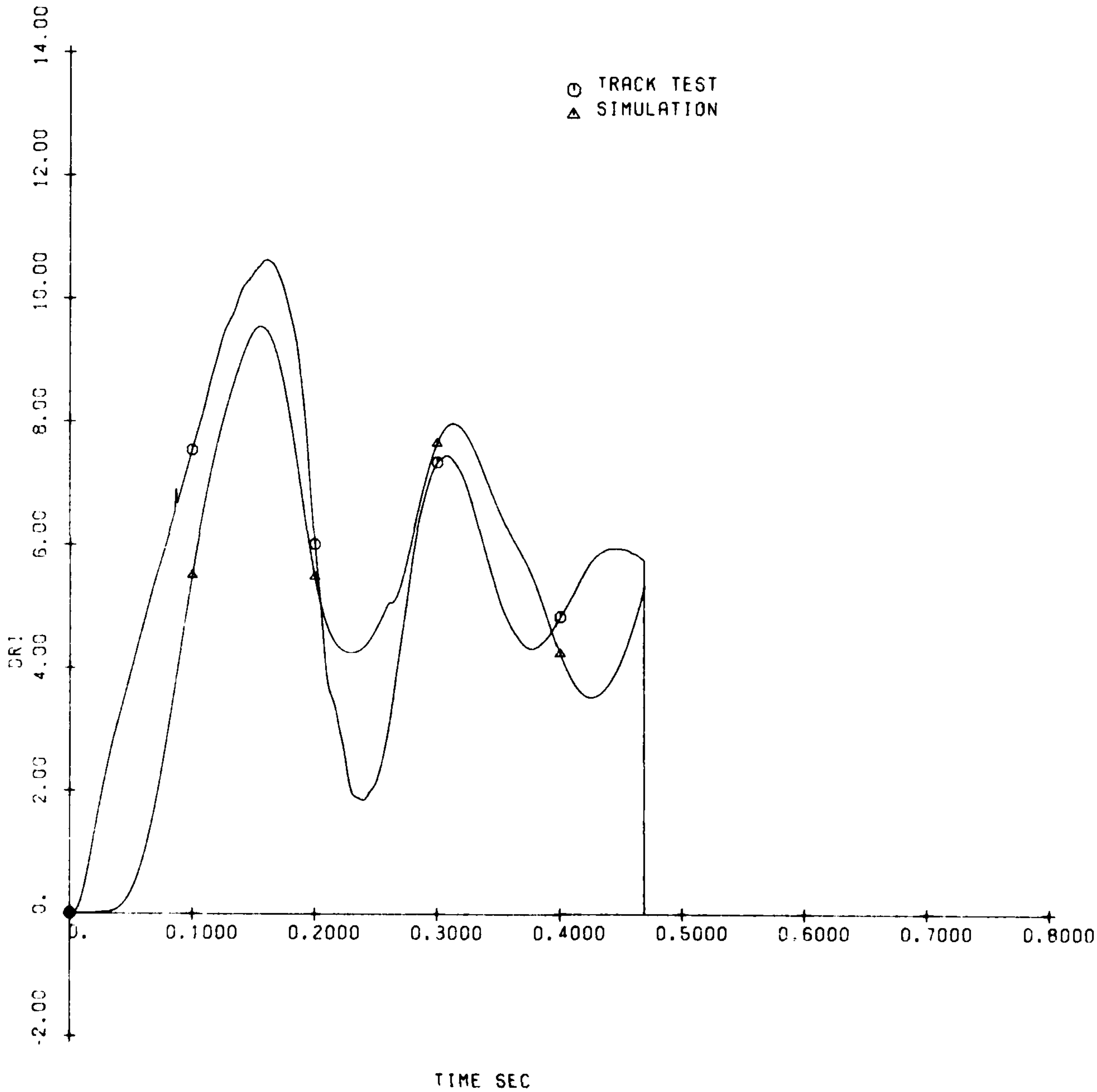


Figure 30. DRI vs TIME 49E-11A

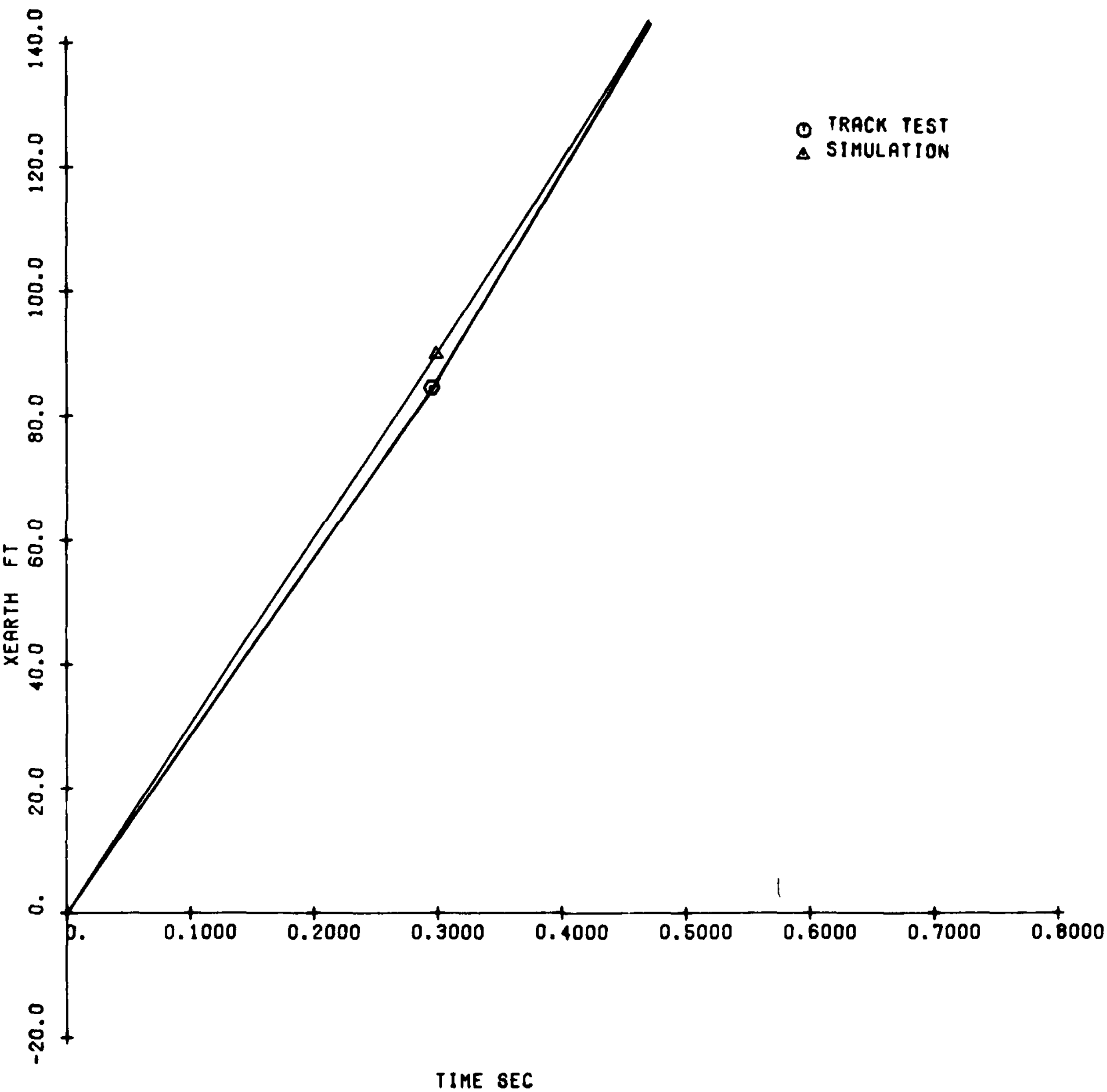


Figure 31. XEARTH vs TIME 49E-11A

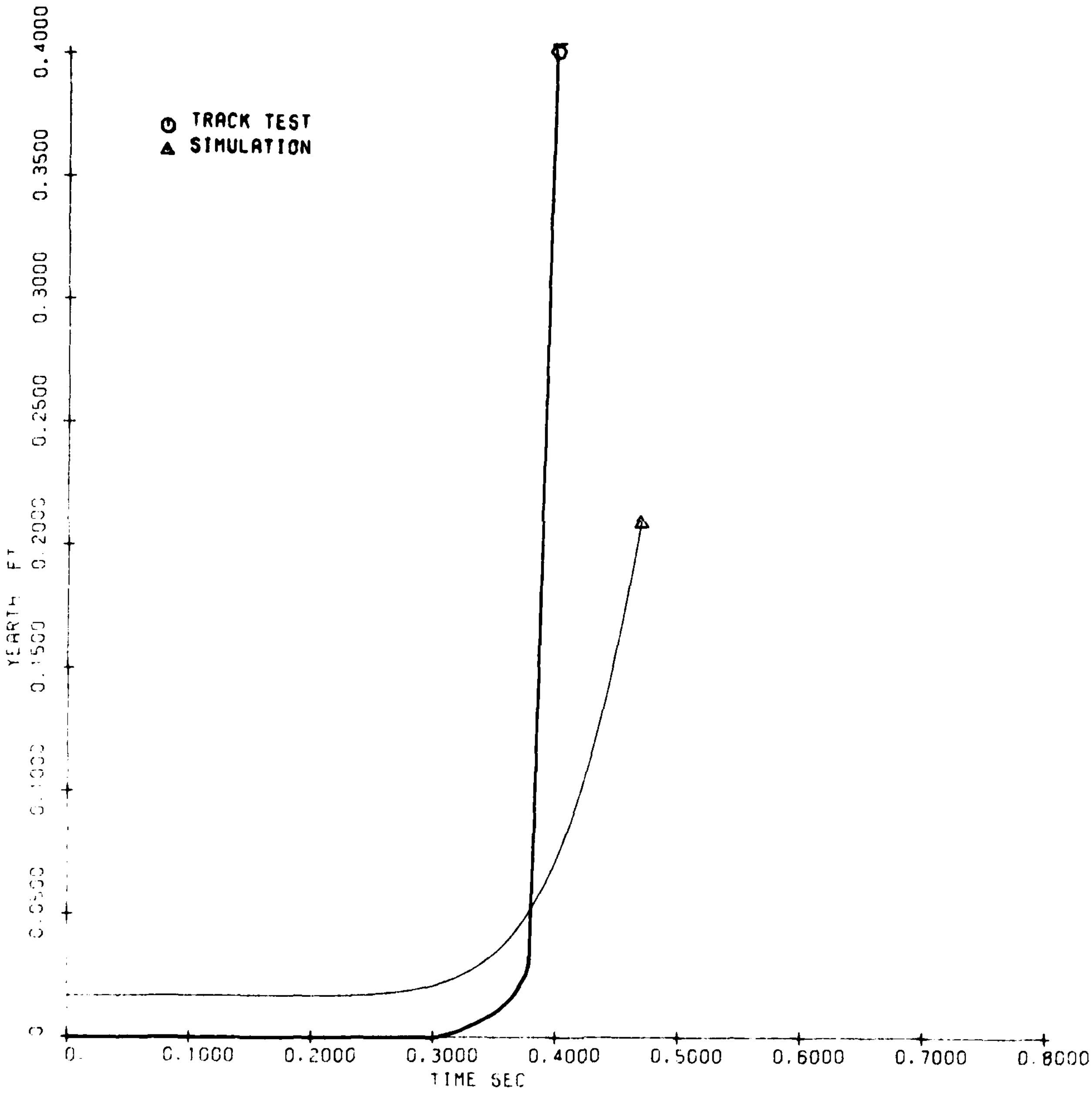


Figure 32. YEARTH vs TIME 49E-I1A

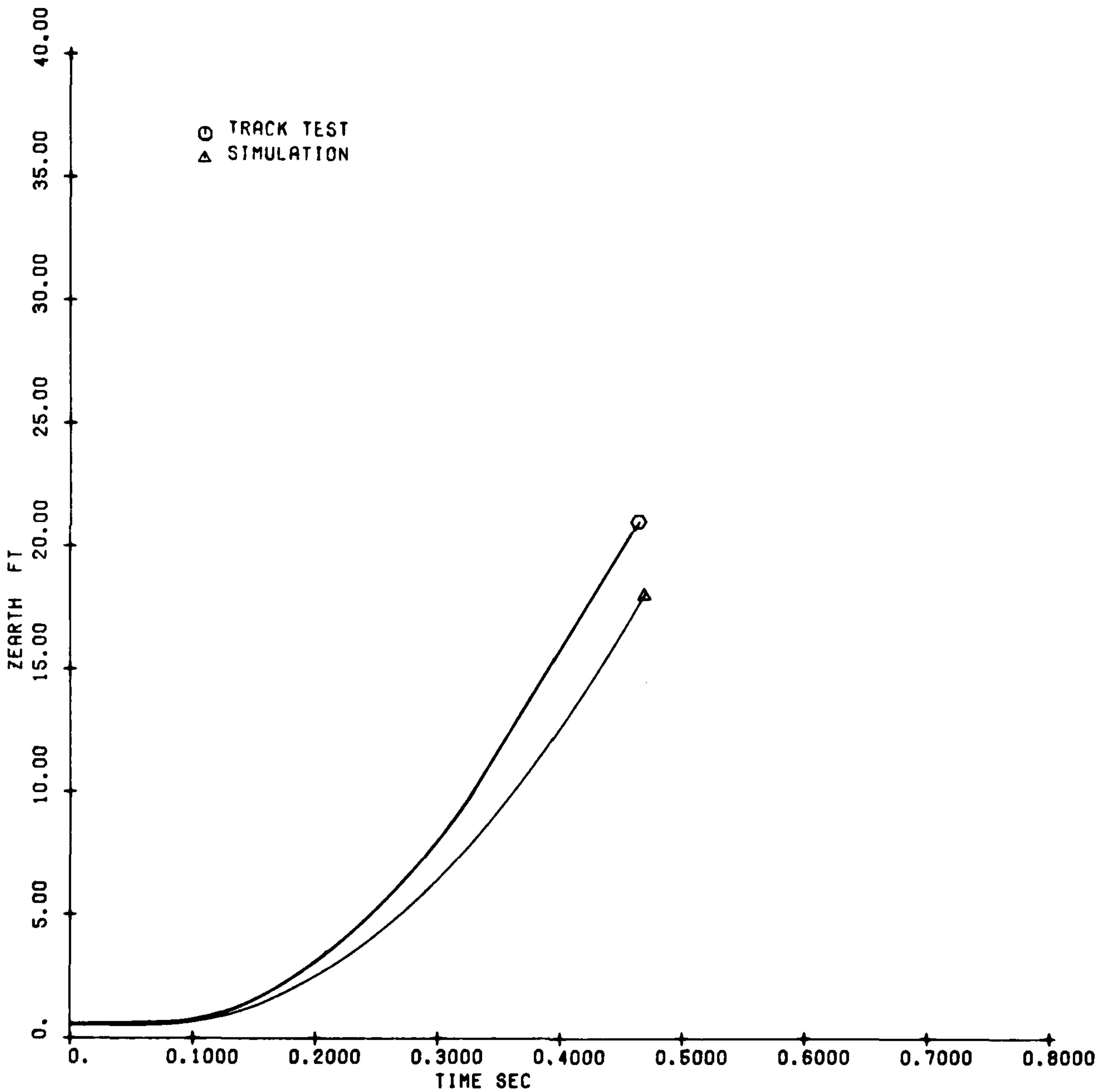


Figure 33. ZEARTH vs TIME 49E-11A

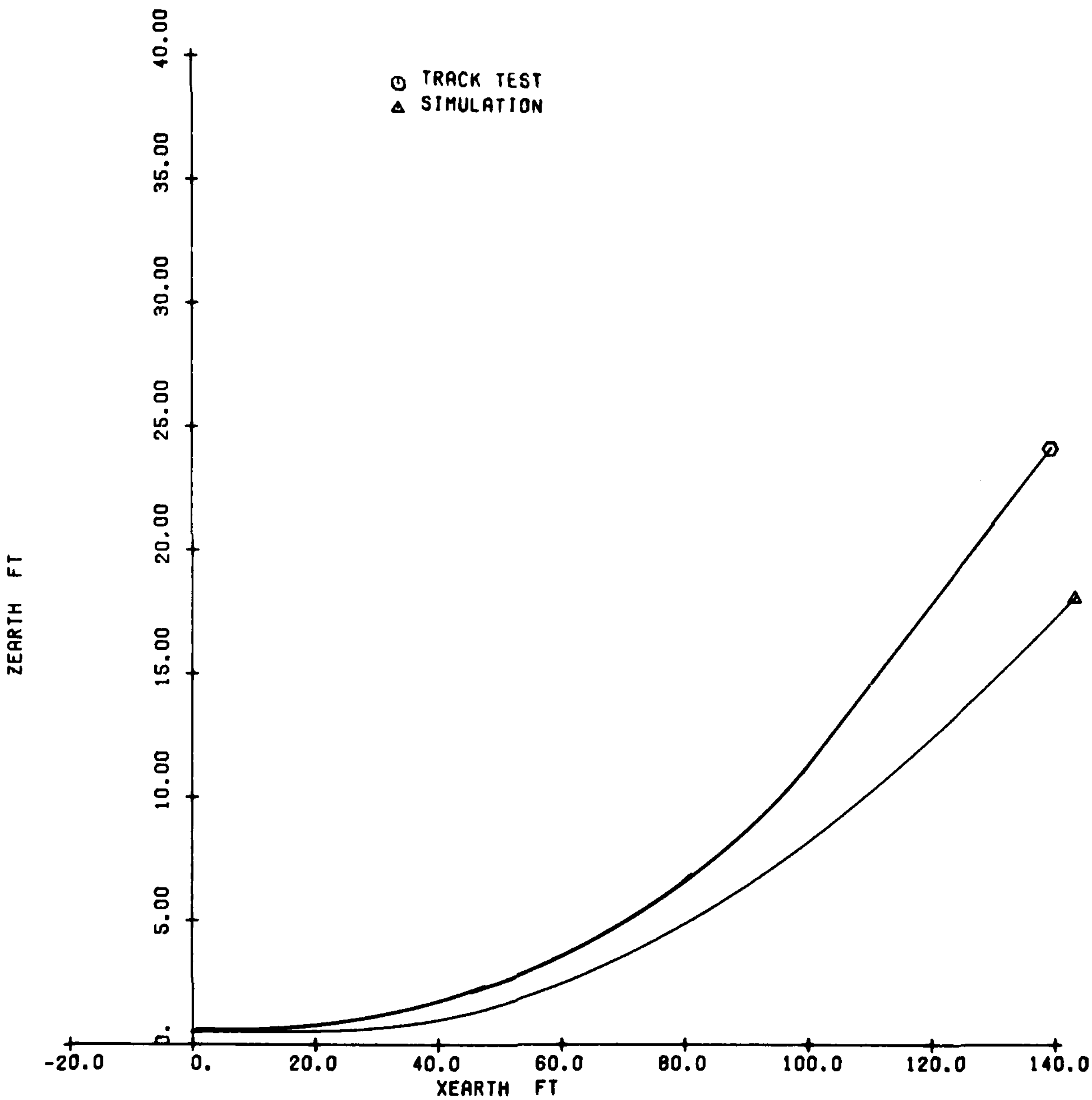


Figure 34. ZEARTH vs XEARTH 49E-11A

SECTION V

CONCLUSIONS

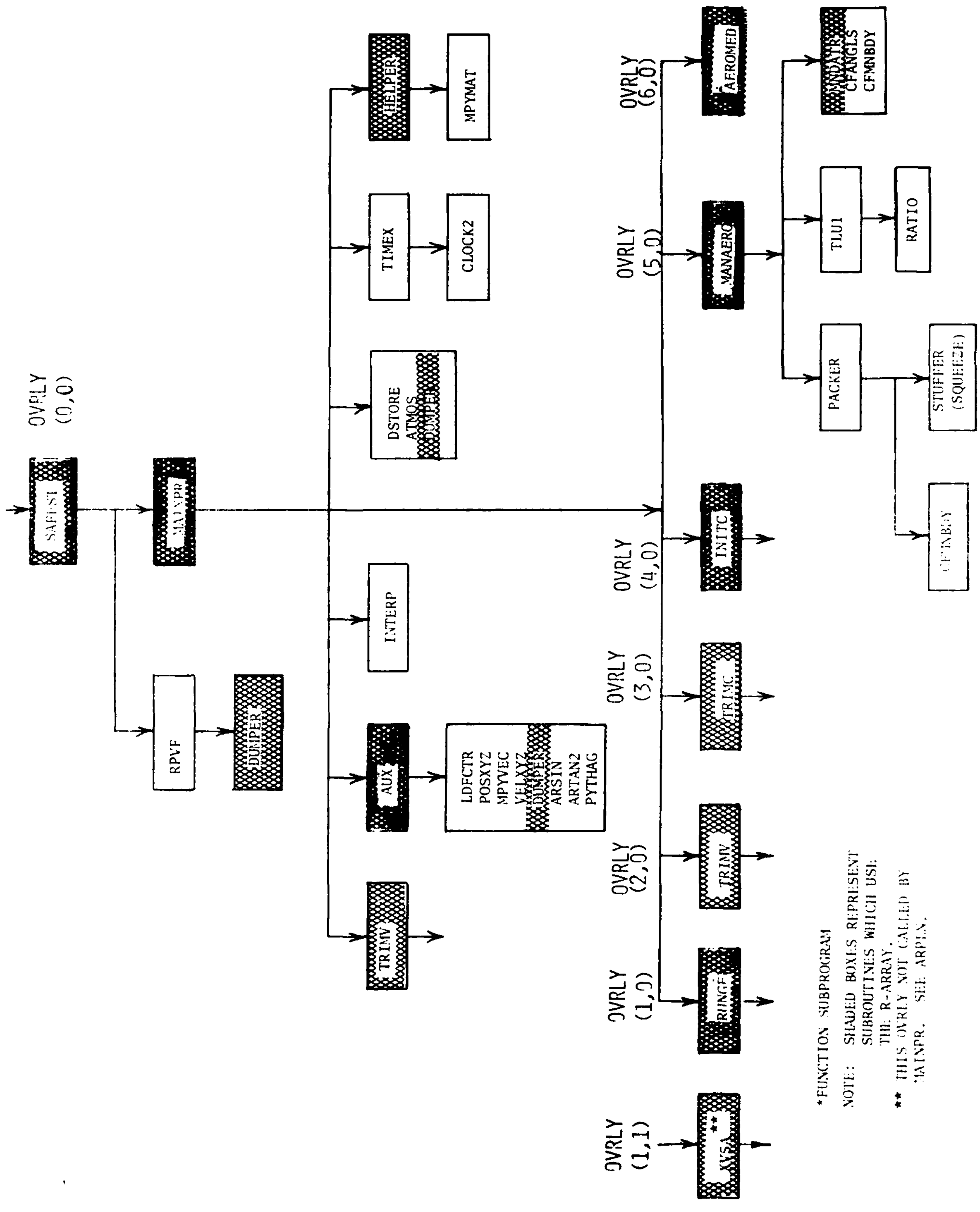
The preliminary correlation evaluated for the SAFEST computer program identifies significant technical capabilities and reveals specific areas for future improvements. The accurate simulation of the accelerations upon the ejecting crewperson and the resulting determination of the DRI value represents a capability useful in the evaluation of current escape systems, planned ejection seat modifications, and proposed system performance relative to the human tolerance capability. The demonstrated prediction capability for angular rates during the high-speed case are essential and desirable to achieve the appropriate acceleration history for each axis of the seat crewperson combination. The discrepancies previously noted in the predicted rates for the low-speed case may be corrected by acquiring more accurate input data for the rail rigidity matrix. Additionally the rates which develop after seat and crewperson launch from the rails compare in trend only and not in actual magnitude with corresponding track test data (see Figures 26, 27, and 28). Although the low-speed track test 49E-I1A utilized basically the same dummy crewperson as the high-speed-case 49E-J1F, the ballast on the dummy crewperson was purposely shifted to provide a low c.g. location to create a test in which the c.g. was below the rocket thrust line.

A comparison of the combined seat and crewperson c.g. location from the SRP seat back axis in Table 3 for the track test with the c.g. location for the computer input from Table 6 (see initial conditions) exhibits a difference of 0.38 inch in the X axis toward the SRP and a 2.37-inch difference in the Z axis away from the SRP. The anticipated result of utilizing the data for a high c.g. relative to the thrust line for simulation of a case in which the c.g. location was actually 0.02 inches below the thrust line was an increase in the computer predicted rates developed after seat and crewperson launch from the rails as compared to track test data. Although the rates for the simulation do increase, the magnitudes are small compared to the actual data. The rail flexure effects previously discussed in conjunction with the inertia of the system overshadow the c.g. thrust line offset discrepancy anticipated.

The simulation discrepancies, which are attributed to input data estimates, warrant future determination through test and analysis of recovery parachute mortar propellant values, accurate c.g. and inertia information of actual instrumented dummy crewperson immediately prior to track test. Additionally, continued effort to improve the dynamic modeling for drogue chute lines and recovery chute deployment forces are needed to result in a complete simulation program capable of system analysis from catapult ignition through full parachute recovery.

APPENDIX A

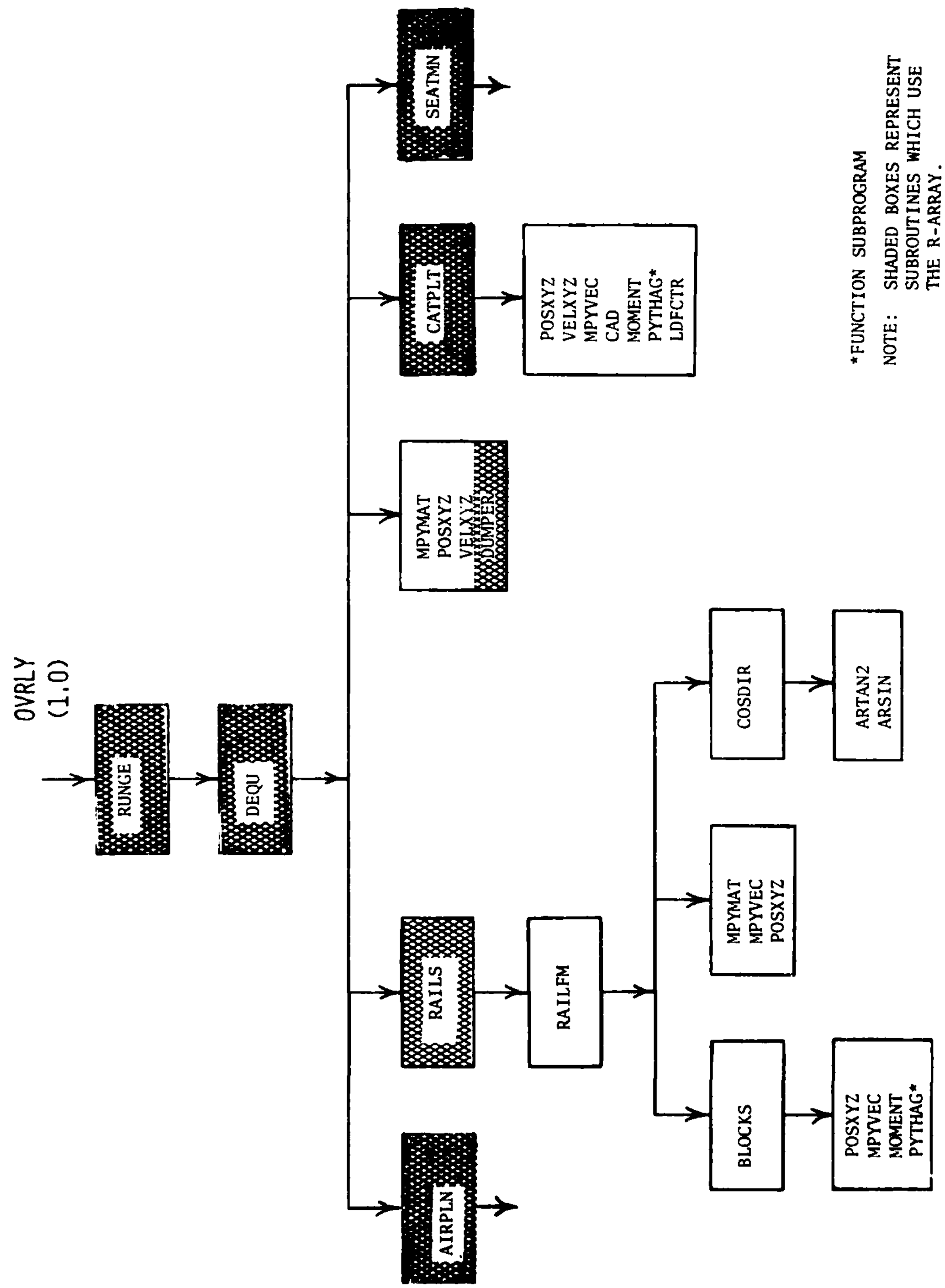
SAFEST FLOW CHART

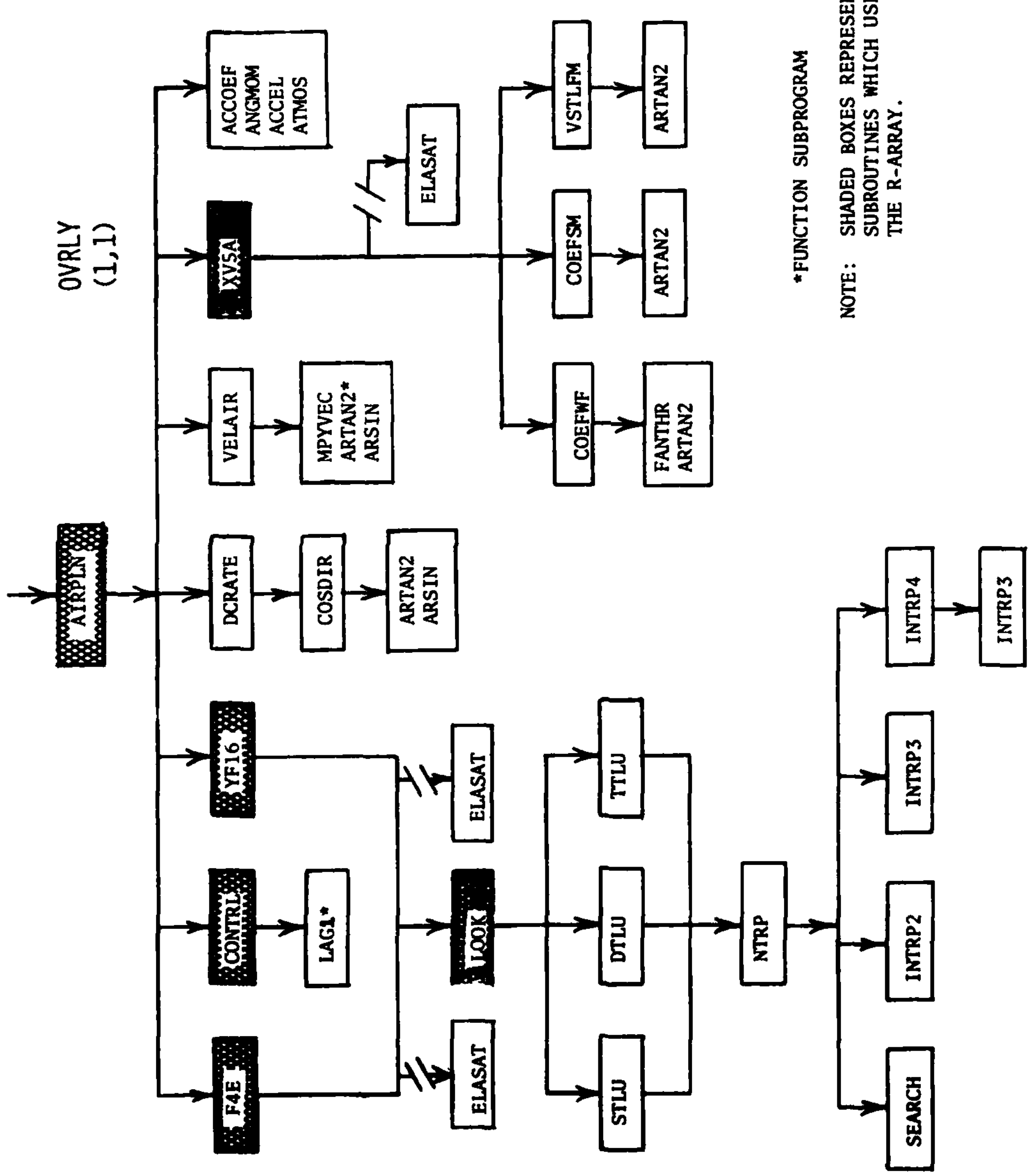


*FUNCTION SUBPROGRAM

NOTE: SHADED BOXES REPRESENT SUBROUTINES WHICH USE THE R-ARRAY.

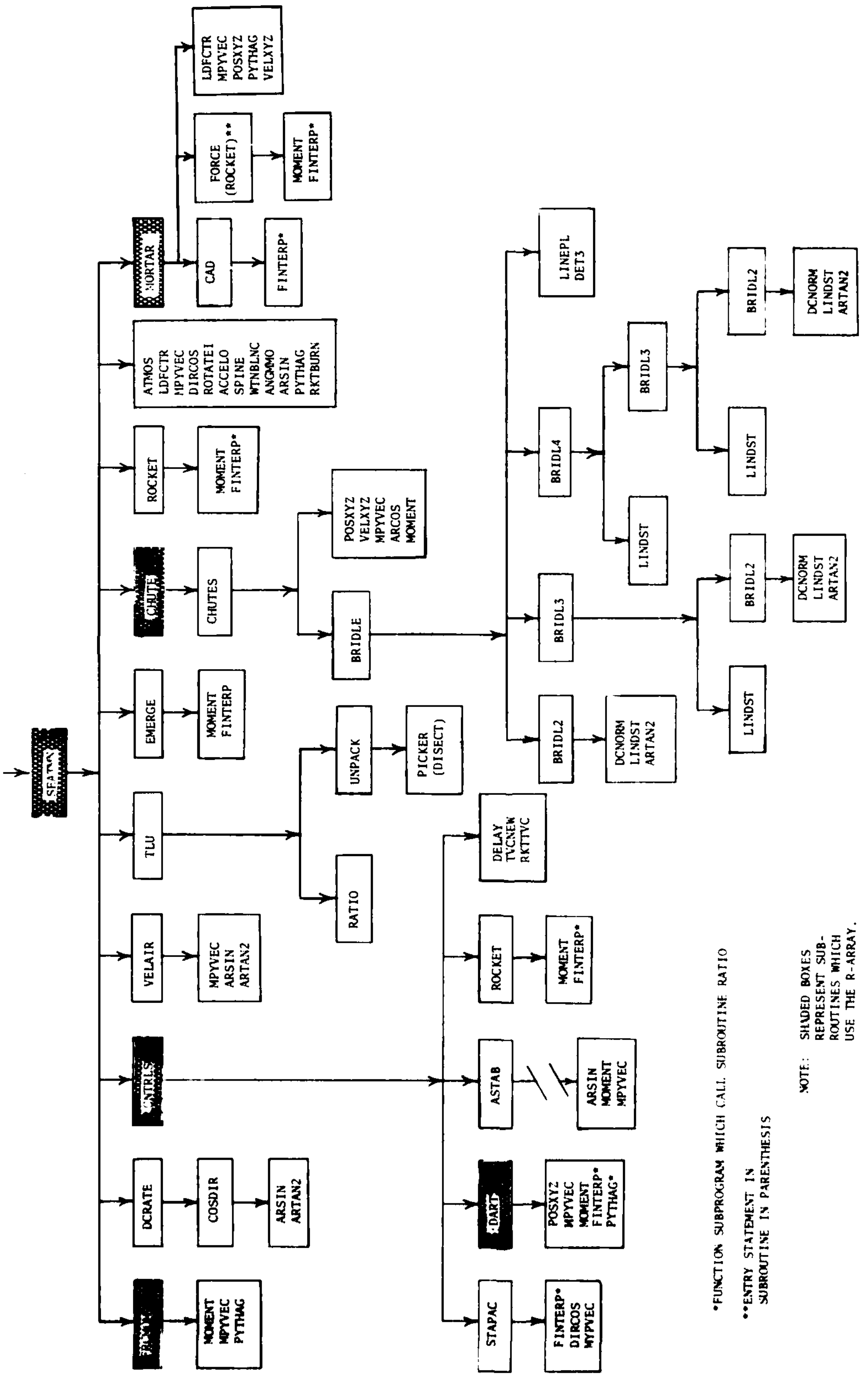
** THIS OVRLY NOT CALLED BY MAINPR. SEE ARPLN.


OVRLY (1.0)
RUNGE
DEQU
AIRPLN
RAILS
RAILFM
BLOCKS
POSXYZ
MPYVEC
MOMENT
PYTHAG*
MPYMAT
MPYVEC
POSXYZ
COSDIR
ARTAN2
ARSIN
MPYMAT
POSXYZ
VELXYZ
DUMPER
CATPLT
POSXYZ
VELXYZ
MPYVEC
CAD
MOMENT
PYTHAG*
LDFCTR
SEATMN
*FUNCTION SUBPROGRAM
NOTE: SHADED BOXES REPRESENT SUBROUTINES WHICH USE THE R-ARRAY.



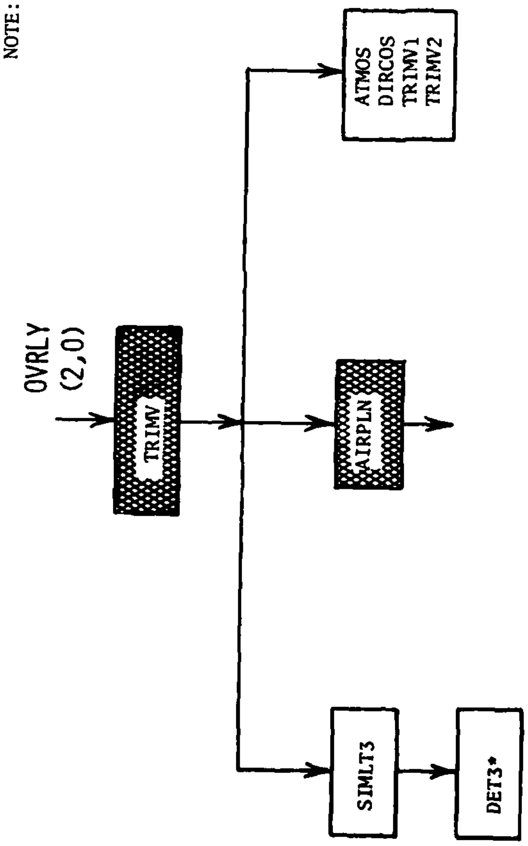
*FUNCTION SUBPROGRAM

NOTE: SHADED BOXES REPRESENT SUBROUTINES WHICH USE THE R-ARRAY.



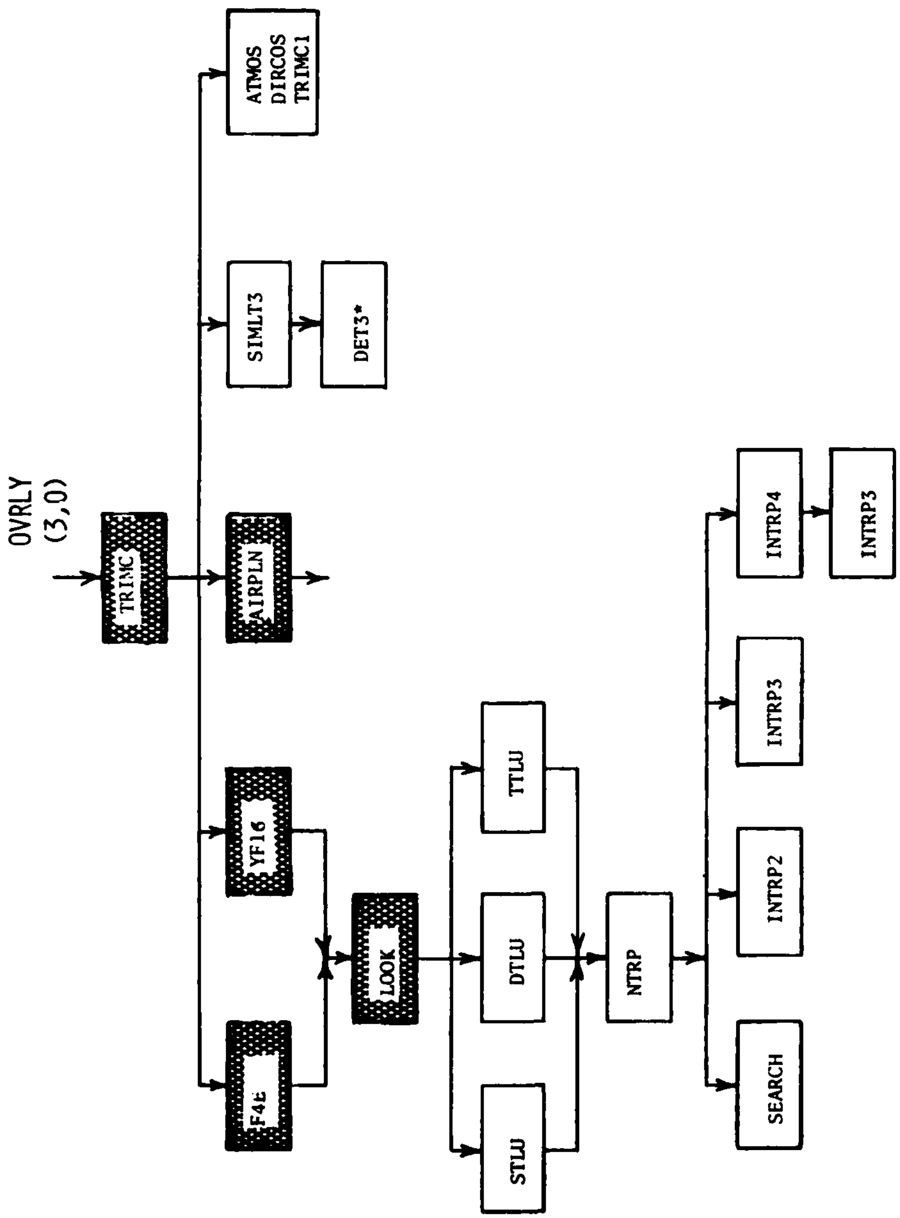
MORTAR
CAD
FINTERP*
FORCE (ROCKET)**
MOMENT FINTERP*
LDFCTR MPYVEC POSXYZ PYTHAG VELXYZ
ATMOS LDFCTR MPYVEC DIRCOS ROTATE1 ACCELO SPINE WTNBLNC ANGMMO ARSIN PYTHAG RKTBURN
ROCKET
MOMENT FINTERP*
CHUTE
CHUTES
POSXYZ VELXYZ MPYVEC ARCOS MOMENT
BRIDLE
EMERGE
MOMENT FINTERP
TLU
UNPACK
PICKER (DISECT)
RATIO
VELAIR
MPYVEC ARSIN ARTAN2
ASTAB
ARSIN MOMENT MPYVEC
DCRATE
COSDIR
ARSIN ARTAN2
DART
POSXYZ MPYVEC MOMENT FINTERP* PYTHAG*
MOMENT MPYVEC PYTHAG
STAPAC
FINTERP* DIRCOS MPYVEC
DELAY TVCNEW RKTTVC
ROCKET
MOMENT FINTERP*
LINEPL DET3
BRIDL4
BRIDL3
BRIDL2
DCNORM LINDST ARTAN2
LINDST
BRIDL3
BRIDL2
DCNORM LINDST ARTAN2
LINDST
LINDST
BRIDL2
DCNORM LINDST ARTAN2
*FUNCTION SUBPROGRAM WHICH CALL SUBROUTINE RATIO
**ENTRY STATEMENT IN SUBROUTINE IN PARENTHESIS
NOTE: SHADED BOXES REPRESENT SUBROUTINES WHICH USE THE R-ARRAY.

NOTE: TRIMV CALLED FROM MAINPR IS INCLUDED WITHIN THE (0,0) SEGMENT

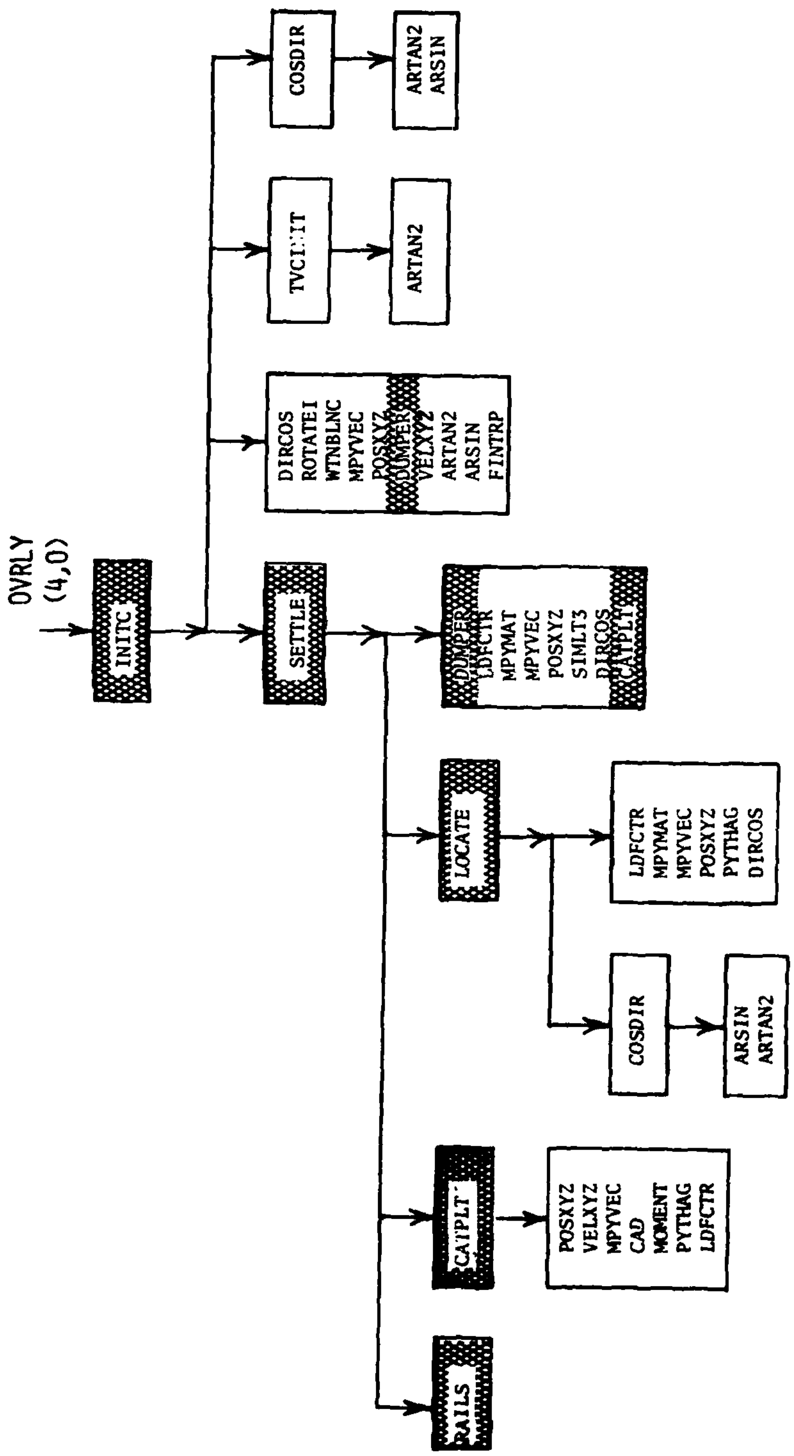


*FUNCTION SUBPROGRAM

NOTE: SHADED BOXES REPRESENT SUBROUTINES WHICH USE THE R-ARRAY.



*FUNCTION SUBPROGRAM
NOTE: SHADED BOXES REPRESENT SUBROUTINES WHICH USE THE R-ARRAY.



*FUNCTION SUBPROGRAM

NOTE: SHADED BOXES REPRESENT
SUBROUTINES WHICH USE
THE R-ARRAY

APPENDIX B

SEAT AND CREWPERSON C.G. AND INERTIA DATA

SIMULATED HITECH 49E-I1A EJECTION

COMBINED SEAT & CREWPERSON WEIGHT, INERTIA, & CENTER OF GRAVITY

EVENT	TIME SEC	WT LBS	IXX SLUG-FT^2	IYY SLUG-FT^2	IZZ SLUG-FT^2	IXY SLUG-FT^2	IXZ SLUG-FT^2	IYZ SLUG-FT^2	XBAR IN	YBAR IN	ZBAR IN
INITIAL CNDTNS	0.000	407.5	18.39	20.30	6.26	0.33	3.27	0.08	5.84	0.20	-11.38
SEAT LAUNCH OFF RAILS	0.246	407.04	20.48	22.48	6.35	0.31	3.87	0.01	5.79	0.23	-11.86
RECOVERY MORTAR STRIPOFF	0.258	383.92	16.25	17.78	5.85	0.35	2.53	-.13	6.41	0.19	-10.22

SIMULATED HITECH 49E-J1F EJECTION

COMBINED SEAT &(CREW PERSON)WEIGHT, INERTIA, & CENTER OF GRAVITY

EVENT	TIME SEC	WT LBS	IXX $SLUG\text{-}FT^2$	IYY $SLUG\text{-}FT^2$	IZZ $SLUG\text{-}FT^2$	IXY $SLUG\text{-}FT^2$	IXZ $SLUG\text{-}FT^2$	IYZ $SLUG\text{-}FT^2$	XBAR IN	YBAR IN	ZBAR IN
INITIAL CNDTNS	0.000	407.50	18.39	20.30	6.26	0.33	3.27	0.08	5.84	0.20	-11.39
DROGUE SLUG DEPLOYMENT	0.181	406.50	18.34	20.22	6.22	0.32	3.28	0.80	5.87	0.21	-11.27
DROGUE CHUTE DEPLOYMENT	0.233	398.17	18.29	20.00	5.97	0.25	3.29	0.09	6.09	0.30	-11.40
SEAT LAUNCH OFF RAILS	0.244	397.95	18.28	19.94	5.92	0.25	3.25	0.10	6.12	0.30	-11.38
ROCKET BURNOUT	0.571	392.98	18.13	19.58	5.72	0.20	3.09	0.01	6.31	.36	-11.35
RECOVERY CHUTE MORTAR STRIPOFF	1.222	370.08	16.05	17.22	5.41	0.26	2.41	-.12	6.82	.29	-10.29

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